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RAIL WEAR COST MODEL
USER'S MANUAL

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prepared for
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17. Abstract

The CIGGT Rail Wear Cost Model was initially conceived as a response to a growing need for methods of quantifying the increased burden on rail observed to accompany heavy unit train movements in high-curvature territory. The performance of this task entailed the construction of a computer model to carry out a detailed trace of rail wear causality to arrive at estimates of service-specific avoidable costs. It was necessary to equip the methodology with the capability to deal with a large number of variables in recognition of the heterogeneous nature of railway traffic and track. The result was a general-purpose model suitable for the estimation of the impact on rail wear rates, rail lives and rail costs of a large number of system design changes. This report has been prepared as a guide for the user of the CIGGT Rail Wear Cost Model.

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17. Résumé

Le modèle d'usure des rails du CIGGT a été conçu au départ dans le but de répondre au besoin de plus en plus pressant de quantifier l'usure accélérée des voies accueillant un trafic lourd de trains-blocs et caractérisées par un tracé particulièrement sinueux. Il fallait pour cela développer un modèle informatique capable de simuler la trace du passage d'une roue de wagon, de représenter l'usure consécutive des rails et, enfin, de déterminer les économies réalisables par une modification des conditions de service et de la nature du trafic, destinée à freiner l'usure constatée. Il fallait aussi que le modèle soit assez puissant pour pouvoir prendre en compte le nombre considérable de variables nécessaires pour représenter la diversité des trafics et des voies ferroviaires. Tout ceci mis ensemble a débouché sur un modèle d'applicaton générale capable de prévoir les conséquences d'un nombre important de modifications du réseau sur l'usure des voies, leur durée utile et les frais d'entretien du réseau. Le présent rapport est en fait le guide d'utilisation du modèle mis au point par le CIGGT.

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1. INTRODUCTION

The objective of the Road Maintenance Cost Model research conducted from 1975 to 1982 was to formulate a methodology for the estimation of route-specific and service-specific unit costs for road maintenance. A computer model, which simulates the mechanisms by which rail deteriorates under traffic to levels where replacement of the rail is normally required, was constructed and improved through some sixteen versions. Methodologies for the estimation of deterioration and related costs for ties and ballast with changes in traffic and track condition were also developed. This work was performed at the Canadian Institute of Guided Ground Transport with the support of Canadian National, Canadian Pacific Ltd. and Transport Canada.

1.1 RAIL WEAR

The CIGGT Rail Wear Cost Model (RWCM) was initially conceived as a response to a growing need for methods of quantifying the increased burden on rail observed to accompany heavy unit train movements in high curvature territory. The performance of this task entailed the construction of a computer model to carry out a detailed trace of rail wear causality to arrive at estimates of service-specific avoidable costs. It was necessary to equip the methodology with the capability to deal with a large number of variables in recognition of the heterogeneous nature of railway traffic and track. The result was a general purpose model suitable for the estimation of the impact on rail wear rates, rail lives and rail costs of a large number of system design changes.

The Rail Wear Program accepts, as input, variables describing operating statistics, track geometry parameters, track quality standards, and the nature of vehicles in the traffic mix. These variables are used to characterize the dynamic wheel/rail interaction for each vehicle type and rail contact location. Estimates of the rates of abrasive/adhesive wear and cumulative plastic deformation on the high- and low-rail heads, the high-rail gauge-face and at the joint are made. Wear rates and cumulative deformation are summed at each contact location for all wheels of a single vehicle and all vehicles

in the traffic mix. This is then compared to the specified head, side, and rail-end wear allowances, yielding an estimated rail service life. The service life estimates are then used to generate a measure of equivalent annual (replacement) cost. By deleting each homogeneous segment of traffic in turn, repeating the wear simulation, renewal cycle and equipment annual cost, and comparing with that attributable to the total traffic, decremental cost measures are obtained for each segment. These can be divided by the tonnage of each segment to obtain service-specific unit costs, or added together to obtain a measure of total variable cost.

This report has been prepared as a guide for the user of the CIGGT Rail Wear Cost Model. An overview of the structure of the model is given in Section 2, with more detailed discussion of the individual components in Section 6. Sections 3 and 4 cover input parameters; Section 5, the output options. The calibration of the model is discussed in Section 7. A full parameter list with definitions is found in Appendix A. The remaining appendices provide additional information for use of the model and analysis of the results, such as flowcharts, sample input and sample output.

2. OVERVIEW

2.1 PROGRAM CONTROL

There are four major subsections in the program. All activity in the CIGGT Rail Wear Cost Model is controlled from the main program, ROOT. LOADER and the routines it calls handle data input, setting of calibration factors, and determination of train mode (normal, dynamic braking, or air brakes). PASS1 calls all routines involved in the determination of forces, slip rates, wear, and batter rates for each of the contact locations, and all routines involved in determining traffic conditions. PASS2 calls the routines which delete traffic classes, determine new lives, and calculate incremental and marginal costs associated with deleted classes. PRNT prints wear and life summaries. The structure of the program is shown in Figure 2.1.

2.2 PROGRAM FLOW

The model proceeds in the following way. After reading in all input data associated with the current case (e.g. curve), it calculates the total rolling resistance, available horsepower, available dynamic braking, and so on. From these calculations it decides if the average train in each direction is being pulled by the locomotives, or if the locomtives are dynamic braking, or if the locomotives and cars have air brakes set. It converts this information, plus any imbalance in superelevation, into the gross forces acting on each car type in each direction. This is further broken down to the angle of attack and L/V on each axle of each car type in each direction. Each axle is put into dynamic equilibrium and creep rates, friction coefficient and normal forces are computed at the high-rail head, the low-rail head, and the high-rail gauge-face. Next the routine estimates the dynamic loads associated with normal force and adds the appropriate amount to the normal forces.

At this point it is possible to calculate wear rates for each contact patch on each axle of each car type in each direction. This proceeds by calculating the maximum contact stress and contact patch dimensions. Next, the individual wear rates are computed based on

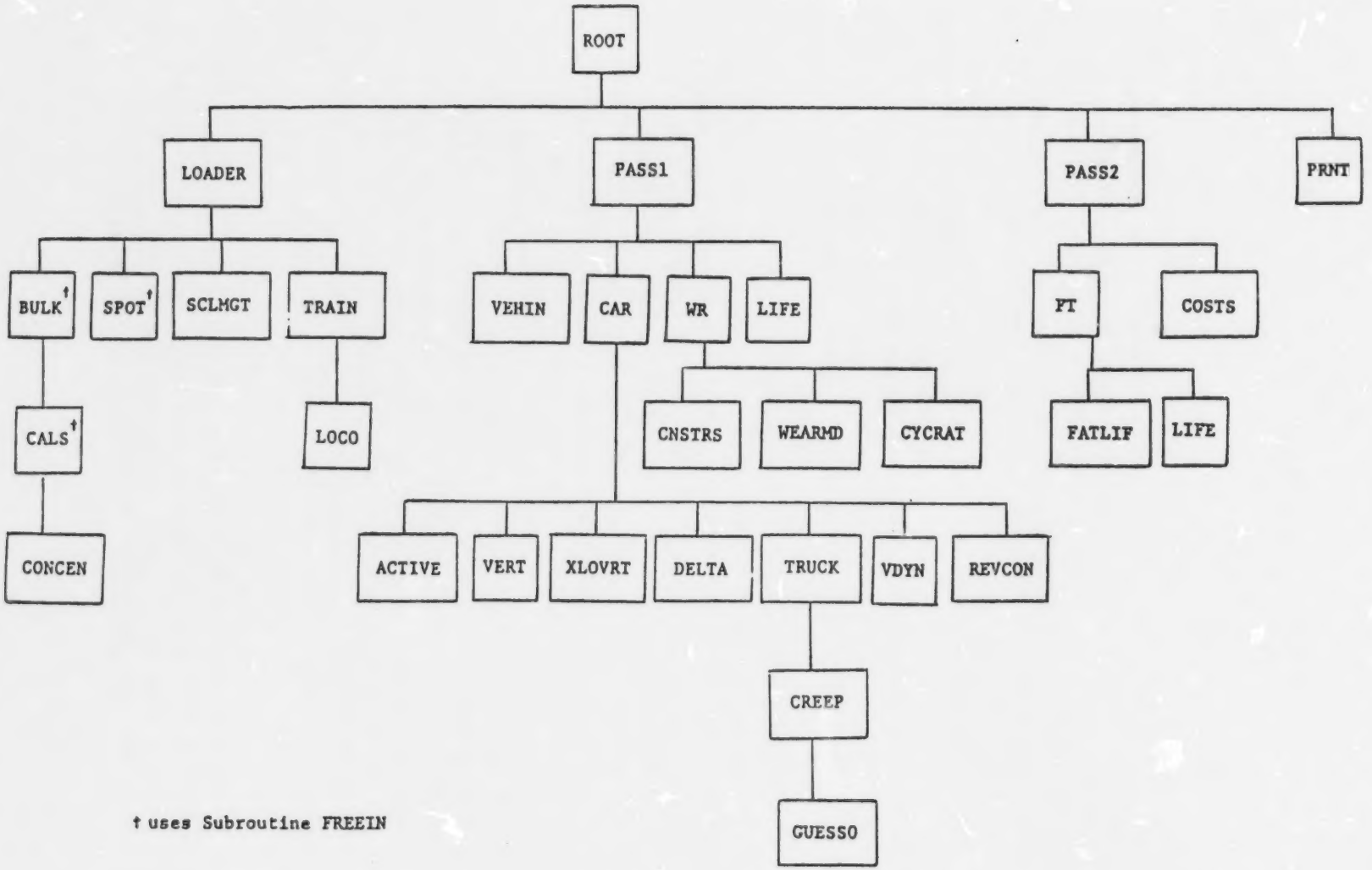


Figure 2.1 CIGGT Rail Wear Cost Model

friction coefficients and slip rates computed earlier. Dynamic loads are estimated both at rail or weld joints and elsewhere along the rail, thus the process is repeated to calculate joint/weld batter. Also, once the stresses are known, the routine can calculate the fatigue cycles associated with each car type, etc. After adding all this up, the routine estimates wear and batter rates and fatigue lives. Using this information, it can estimate incremental and marginal costs associated with this rail replacement.

2.3 PROGRAM SETUP

The CIGGT Rail Wear Cost Model is written in FORTRAN IV program language. Initial development was carried out on a Burroughs 6700, with subsequent modification for PDP11-03 FORTRAN. The program is now available in an IBM-compatible form as well as PDP11 form.

To run the program on any system, it will be necessary to declare a number of input and output files. The form of these declarations will vary with the system used. For the IBM version, FILE 1 is the input run data file containing the 'bulk' data, followed by the 'spot' data; FILE 2 is the debug output file; FILE 3 is the output scratch file; FILE 4 is the input calibration data file, FILE 5 is the input stress tables file; and FILE 6 is the output listing file.

For running the IBM version of the CIGGT Rail Wear Cost Model under the VM/SP Conversational Monitor System, the EXEC used appears as:

```
FILEDEF * CLEAR
FILEDEF FT01F001 DISK &1 DATA A
FILEDEF FT02F001 DISK DEBUG LISTING A (LRECL 133
FILEDEF FT03F001 DISK FILE3 BINARY A (RECFM VS
FILEDEF FT04F001 DISK CAL DATA A
FILEDEF FT05F001 DISK STRESS TABLES A (RECFM VS
FILEDEF FT06F001 DISK &1 LISTING A
RMCM
```

When installing the program on a new system, it will be necessary to build a stress concentration file for the binary on the new system. The code to do this is in subroutine CONCEN in the program. It is well worth the IO to establish a saved file, even on a big system. To initiate the building of the stress tables, run the program with a

blank line at the beginning of each of the data and calibration files. For running under VM, the EXEC becomes:

```
FILEDEF * CLEAR
FILEDEF FT01F001 DISK STRESS DATA A
FILEDEF FT02F001 DISK DEBUG LISTING A (LRECL 133
FILEDEF FT03F001 DISK FILE3 BINARY A (RECFM VS
FILEDEF FT04F001 DISK CAL STRESS DATA A
FILEDEF FT05F001 DISK STRESS TABLES A (RECFM VS
FILEDEF FT06F001 DISK STRESS LISTING
LOAD RMCM
START
```

where STRESS DATA is a file of two blank lines.

3. DATA INPUT

The input data file is structured in such a way as to permit the performance of large runs and to provide flexibility in the parameters which can be altered. It also permits the naming and storage of data sets for future reference.

There are two major ways in which data are loaded into the program. The first is in the 'bulk' data section. It is used to load the track, traffic, maintenance, and cost conditions for the initial case in a run of the program. The second is in the 'spot' data section of the loader routine. Spot-data are used to make changes to the base data set. All data changes made through the loading of spot-data are effective for all the cases following the making of the change in a run unless changed again by later spot-data input.

See Section 6.3 for a description of subroutine BULK, Section 6.6 for a description of Subroutine SPOT, and Appendix D for sample input data files.

DATA DECK FORMAT:

The RWCM data deck is composed of three parts:

- bulk data cards = baseline case description
- car specification cards = traffix mix for entire run
- spot-data cards = subsequent cases using the same traffic mix.

BULK DATA CARDS:

First card (formatted: 8I1,72A1)

```
0        1         2         3         4         5         6
12345678901234567890123456789012345678901234567890123456789

1311111 THIS IS A USER LABLE TO THE END OF THE CARD
```

where:

- column 1 asks for input data echo
- column 2 controls car summaries
- column 3 controls wear summaries
- column 4 controls batter summaries
- column 5 turns on/off the fatigue calculation
- column 6 controls the engineering summary
- column 7 controls the second pass
- column 8 is reserved for future expansion

Past column 8 is a label printed with the data at the top of each page.

A description of the output options is given in Section 5.

2nd card (free format):

TOTMGT	total traffic (+ = scale to this, 0 = program adds, - = scale non-locos)
NCARS(1)	car types in forward direction -- see car specification section
NCARS(2)	car types in backhaul direction (may be 0 for 0 grade)

3rd card (free format):

DCURV	track curvature in degrees
SE	superelevation (+ = in inches, - = in mph, -1 = use first speed)
GRAD	per cent grade

4th card (free format, optional -- if you specify XMGT of locos leave it out):

CPL(1) cars per locomotive in forward direction (XMGT of locos = 0)

CPL(2) cars per locomotive in backhaul direction (XMGT of locos = 0)

WPR[1] or:

DG(1) design grade in forward direction (no locos specified)

DG(2) design grade in backhaul direction (no locos specified)

5th card (free format):

IRAIL rail type (1,2 = jointed, 3,4 = CWR, 2,3 = normal, 1,4 = hardened)

RI rail inertia (132 lb = 88.2,[2] 115 lb = 65.6, 100 lb = 49.0, 85 lb = 29.5)

U track modulus in lbf/in/in (good = 4000, average = 2500, poor = 1000, concrete ties = 15000)

TRV vertical irregularity (main line = 1.0 in., branch line = 2.0 in.)

TRL lateral irregularity (main line = 0.75 in., branch line = 1.5 in.)

DIP dip joint angle (good = 0.010 rad, average = 0.015 rad, poor = 0.20 rad)

RO support factor (CWR = 1.0, main line = 0.6, branch line = 0.4)

MR rail mass/ft (132 lb = 44, 115 lb = 38.33, 100 lb = 33.33, 85 lb = 28.33)

MT tie mass/ft (wood = 61.56 lb, concrete = 153.7 lb)

---

1 WPR, the weight-to-power ratio, is calculated in the program. At one time it was entered directly.

2 In keeping with the practice of North American railways, all parameters read into the program are in British units. As conditions in the industry change, modifications to the program will be made in order that the metric equivalents are accepted as input. For conversion purposes, note that 1 inch = 2.54 cm, 1 lbm = 0.4536 kg and 1000 lbf/in/in = 6.8994 MN/m/m.

GWG	gauge widening (good = 0.0 in., poor = 1.0 in.)
LUBRIC	lubrication indicator (0 = no lubrication, 1 = lubrication)

6th card (free format, optional -- for option 6 = 0.2 and option 7 = 0 leave out):

TWA	transposal wear allowance (132 lb = 0.75, 115 lb = 0.5, 100 lb = 0.375)

7th card (free format, option -- for option 7 = 0 leave out):

ROK	return on investment (typical = 0.15)
DELTC	price escalator (typical = 0.06)
UCOST	replacement cost/mile (typical = 127., $1000/mile)
SALV	salvage value/mile (typical = 33., $1000/mile)

Car specification cards:

There are NCARS(1) + NCARS(2) of these cards defining the traffic mix. Each card is configured as follows:

ITYPE	car type indicator (1 = loco, 2 = freight, 3 = passenger)
NAXLE	number of axles/bogie (2 or 3 for locos, 2 otherwise)
PO	load per wheel in pounds
WUE	unsprung weight per wheel in pounds (1600 for 70 ton, 2000 for 100 ton, 5484 for loco)
R	wheel diameter in inches (32 for 70 ton, 36 for 100 ton, 40 for loco)
XMGT	MGT/year of the car type (0 for locos using CPL on card 4)
V	speed in mph
H	centre of gravity height in inches (loaded = 90, empty = 55)

Spot-data cards:

The bulk data and car specification cards define a complete case. It is run through the program and then the program returns to the data file to look for any spot-data cards. Any of the variables that do not change the traffic mix can be individually changed and the case rerun. All changes are cumulative and the procedure can be repeated as many times as desired.

Variables are changed by entering a card with the (variable name) = (value) written on it. For example, to change the curvature and superelevation, the following card might be used: DCURV=4.,SE=3.5. This would change the curvature to four degrees and the superelevation to 3.5 inches. As many cards as are desired can be used to change variables. When all changes have been made, starting on a new card, enter RUN followed by the new case label. The following variable names are understood by the program:

TOTMGT	RI	RO	TWA	BHN
DCURV	U	MR	ROK	JOINTED
SE	TRV	MT	DELTC	CWR
GRAD	TRL	GWG	UCOST	L
IRAIL	DIP	LUBRIC	SALV	C

To run the next case enter:

> RUN, this is a user case label through 72 characte.s (1 blank required after RUN)

Sample data deck:

```
0000020 BHN 260, 0 DEG CURVE, CWR,    QNS&L DATA              (1st card)
54., 2, 3                                                     (2nd card)
0., -30., 0.                                                  (3rd card)
3, 88.2, 4000., .50, .25, 0.01, 1., 44., 61.65, 0.25, 1       (5th card)
1, 3, 31000, 5484, 40,  1.2, 40, 90        (car specification, forward)
2, 2,  6000, 1995, 36,  8.1, 40, 55        (car specification, forward)
1, 3, 31000, 5484, 40,  1.2, 30, 90       (car specification, backhaul)
2, 2, 32500, 1995, 36, 26.1, 30, 90       (car specification, backhaul)
2, 2, 35750, 1995, 36, 17.4, 30, 90       (car specification, backhaul)
DCUVR=1                                                     (spot data)
RUN BHN 260, 1 DEG CURV, CWR,      QNS&L DATA                (2nd run)
DCURV=2                                                     (spot data)
RUN BHN 260, 2 DEG CURV, CWR,      QNS&L DATA                (3rd run)
```

```
DCURV=3                                                    (spot data)
RUN BHN 260, 3 DEG CURVE, CWR      QNS&L DATA               (4th run)
IRAIL                                                      (spot data)
RUN BHN 350, 3 DEG CURVE, JOINTED, QNS&L DATA               (5th run)
DCURV=4                                                    (spot data)
RUN BHN 350, 4 DEG CURVE, JOINTED, QNS&L DATA               (6th run)
DCURV=5                                                    (spot data)
RUN BHN 350, 5 DEG CURVE, JOINTED, QNS&L DATA               (7th run)
DCURV=6                                                    (spot data)
RUN BHN 350, 6 DEG CURVE, JOINTED, QNS&L DATA               (8th run)
DCURV=7                                                    (spot data)
RUN BHN 350, 7 DEG CURVE, JOINTED, QNS&L DATA               (9th run)
DCURV=8                                                    (spot data)
RUN BHN 350, 8 DEG CURVE, JOINTED, QNS&L DATA              (10th run)
```

The first card is required and is read under format. From then on, all cards are free format. The fourth card, which used to be the weight-to-power card, does nothing if the XMGT of locomotives is specified. Under these circumstances it may be left out (do not put in a blank card). The program can tell if the card has been left out, since there are only two numbers on it and eleven numbers on the next card. The program defaults the card to the values 1.2 and 1.2, typical design grades.

Similarly, unless print option 6 or 7 is set, the TWA does nothing. If it is omitted, the card is defaulted to .75 inches. Also, unless print option 7 is set, the costing card does nothing. The defaults on it are: ROK = .15, DELTC = .06, UCOST = 127.0 and SALV = 33.0. Again, the program can tell that these cards have been left out because of the number of variables on each card.

If the locomotives are included and the XMGT on their car card are set, then there is no need for the fourth card and it may be left out. If locomotives are included, and the XMGT are set to zero on the car card, then the two numbers on the card are assumed to be the number of cars/locomotives in each direction. If the locomotives are omitted, the program will use the card as a design grade and infer enough three-axle locomotives to maintain 7 mph on that grade plus about a 20 per cent pad to allow for an extra locomotive on each run. If the pad is not desired, set the scale factor in the calibration file for LOCO to 2.5 instead of 3.0.

The program allows you to put all the traffic in one direction. If NCARS(2) is set to zero, for example, it runs with all the cars going in the forward direction. This would be appropriate if the grade is zero.

Finally, on the subject of locomotives, there is the matter of TOTMGT. Obviously, if the program calculates the MMGT of locomotives, the user cannot set TOTMGT correctly. There are three options available: if MOTMGT is positive, all the XMGT are scaled so that they add up to TOTMGT; if TOTMGT is zero, the program adds it up, including locomotives; if TOTMGT is negative, all the non-locomotive XMGT are scaled so that they add up to -TOTMGT, and TOTMGT is changed to be positive and reflect the locomotive traffic.

4. CALIBRATION FILE

The calibration file has been separated into a single unit containing all parameters used to calibrate the model, in order to make the calibration process simpler and in order to provide a means by which calibration conditions can be stored and referenced.

Labelling of the calibration files in a systematic way is a recommended procedure. The method which has been adopted for labelling the calibration files at CIGGT links the Rail Wear Cost Model version number and the calibration file number. An example is calibration file V16.01, where the Rail Wear Cost Model number is 16 and the calibration file number is 01.

The CIGGT Rail Wear Cost Model is designed as an interpolative tool which, under close control, may be used to determine wear and costs for different run conditions. The source of much of the program's strength is the fact that it is calibrated to actual wear data.

Calibration of the program is carried out by making adjustments to various parameters in the program. It is of primary importance in this process to ensure that the data loaded into the program properly represent the track and traffic of the system to which the model is to be calibrated. The calibration file contains the parameters which are manipulated to adjust the model results to conform with the condition found in the field.

The following is a sample calibration file:

```
ROAD MAINTENANCE COST MODEL CALIBRATION FILE: VERSION 16.01
MATERIAL PROPERTIES: E=3.0E7, G=1.15E7, POISSON=.3
BRINELL HARDNESS: HIGH=350, LOW=260
TRACK: L=5.0E7, C=8.3E7
UNLUBRICATED FRICTION: HI=.35, LO=.35, GF=.35, MUEMAX=.6
LUBRICATED FRICTION:   HI=.30, LO=.30, GF=.10, MUEMAX=.6
RAIL CURVATURES: HI = 11.5, LO=11.5, GF=1.3, ADJ HI: K=7.5, SUBT=0.0
WHEEL CURVATURES: HI=22., LO=-22., FLANGE=-1.6, LO FOR FF=20.
GEOMETRY FOR CREEP: HI=.32, FLANGE=62.5
MARGINALS BASED ON: .01 MMGT
CAL FOR LOADER: DELTA CURVE=0.4, WORK HRD HI=1.16,5, LO=1.16,5,
                GF=1.099.
CAL FOR LOCO: HP=2.5, LPC=4, SPD=7., EMPO=6250., DYN BRAKING=.0
```

```
CAL FOR ACTIVE: RUNIN/RUNOUT ACCEL=0.000
CAL FOR XLOVRT: OFF BAL SPD=0.3, GAUGE WIDENING=0., BUFF=.0,.0
CAL FOR TRUCK: TRAM=2655., 5.64
CAL FOR REVCON: STD DEV/AXLE=0.43, 1.13, 1.13, CRIT FORCE=99.0
CAL FOR CYCRAT: SE=135, SU=500, MAX CYCLES=5.E7, ONE=1.0, CYCES=1.0
CAL FOR WR: (WEAR) ABR=1.66, PLASTIC=2.5, (BATTER) CWR=1.0,
            JOINTED=.333
CAL FOR WEARMED: ABRASION HI=1.0, LO=1.0, GF=0.75
                 PLASTIC FLOW HI=1.0, LO=1.0, GF=0.75
                 SEVER WEAR=1.0, PLASTIC FLOW THRESHOLD=1.0
CAL FOR FATLIF: LIFE=100, MINER=1.0, OFFSET=50.
```

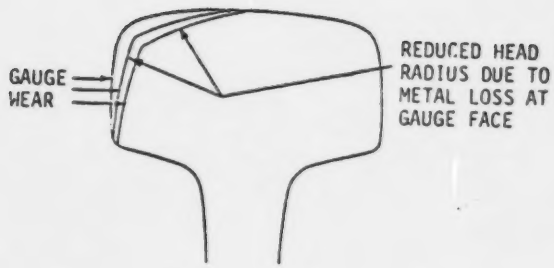
TABLE 4.1

NOTES ON CALIBRATION

Card No.	Title	Parameter	Remarks Regarding Calibration
2	Material Properties	E=Young's Modulus G=Shear Modulus POISSON=Poisson's Ratio	These quantities are not adjusted unless unusual metals are to be used.
3	Brinell Hardness	HIGH=BHN for hardened rail steel LOW=BHN for standard rail steel	The Brinell Hardness number of rail steel is the only way the CIGGT Rail Wear Cost Model handles different rail metallurgies. In cases where it is felt the BHN is not a sufficient indicator of rail properties, a calibrated 'effective' hardness should be determined and used. Under these conditions special attention should also be given to the friction factors.
4	Track	L=Track quality constant C=Hertzian contact deflection constant	L is a constant which indicates the quality of the rail and track structure. By reducing L, the dynamic loads due to surface irregularities are increased and therefore

	Track (cont'd)		the wear rates are increased. Suggested values are $5x10^5$ for poor track, $5x10^6$ for average track, and $5x10^7$ for good track. Care should be taken to ensure that the L value used agrees with the track conditions assumed. C is dependent on the radii of the wheel and rail contacting surfaces. It is not usually changed.
5	Unlubricated Friction	HI,LO,OFF=limiting friction on high-rail, low-rail and gauge-face respectively with no lubrication MUEMAX=limiting friction factors for dry metal on metal contact	The assignment of friction coefficients is determined by the operating conditions. Properties to be considered are humidity, lubrication conditions, and temperature. For unlubricated, the limiting friction factors are usually the same for each contact location. Typical limiting friction values are shown in Figure 6.8.
6	Lubricated friction	HI,LO,GT=lubricating friction on high-rail, low-rail and gauge-face with lubrication	For lubricated, the limiting friction factor on the gauge face is usually less than those for the high- and low-rail heads
7	Rail Curvature	HI,LO,GF=transverse radii for high-rail and low-rail heads and high-rail gauge-face ADJ HI=factors K and SUBT used in adjustment of high-rail head	HI, LO and GF set for partly worn rails. The rail head transverse radii are important quantities in the calculation of contact stresses. In highly-curved track, the gauge wear may have a strong effect on the head radius and therefore on the resulting contact stresses.

Rail Curvature (cont'd)



An empirical equation:

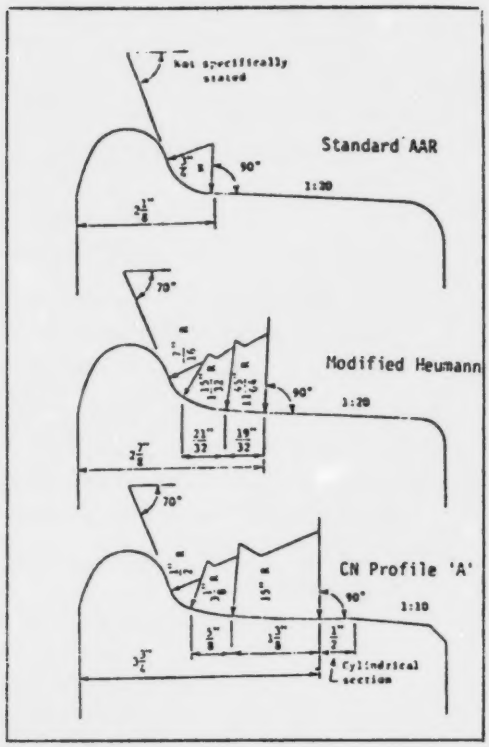
RAD_{Hi} = HI-SUBT x sin (min(k x DCURV, 90°))

is included to account for the effect of gauge wear on the transverse head radius.

In general, it has been found better to perform separate calibration of high- and low-rail head wear directly rather than to use this equation. SUBT has therefore been set to zero.

8	Wheel Curvatures	HI,LO,FLANGE=high, low and flange transverse radii for wheel LO FOR FF=wheel contact radii on low rail with false flanging	The values chosen are for partly-worn wheels and are subject to change with differences in average wheel profile.
9	Geometry	A=radial distance from rail head to flange contact FLANGE=flange angle (degrees) for CN profile FDEL=change in FLANGE for CN profile	These parameters are based on partly-worn rail and partly-worn wheel contact. They will vary with the wheel and rail profile used. Below is a table of new wheel profiles.

Geometry
(cont'd)



1 Wheel Profiles

(All dimensions in inches. Flange details same as for the standard AAR Wide Flange Profile)

10	Marginals	MMGT=number of million gross tons of car class removed for marginal cost	Care should be taken to ensure that the number of a million gross tons of traffic to be removed is not more than the annual traffic in the class.
11	CAL FOR LOADER	DELTA CURVE=curvature to reflect prehunting motion WORKHD=parameters for adjustment by BHN with work hardening	These should be left as is unless a dynamic model of hunting is introduced. For high- and low-rail head, work hardening effect assumed maximum (16 per cent) in flange free region (0° to .84°). Effect is reduced linearly to zero at 5° above flange face. No work harden-

1 P.P. Marcotte, K.J.R. Mathewson, N.W. Caldwell, "Improved Wheel Tread Profiles for Heavy Freight Vehicles," ASME Paper No. 80-RT-3, April 1980.

	CAL FOR LOADER (cont'd)		ing effect assumed for gauge face. These should be changed for different rail metallurgies.
12	CAL FOR LOCO	HP=horsepower scale factor LPC=locomotives per consist SPD=speed on design grade EMPO=wheel load of empty car These are factors for estimating numbers of locomotives required for given design grade.	Horsepower scale factors used to ensure number of locomotives not underestimated. Conditions can be made more severe by reductions in locomotives per consist or increases in speed on design grade. Horsepower scale factor may be increased to increase buffer in estimate.
17	CAL FOR CYCRAT	SE=endurance limit's ratio to BHN SU=ultimate stress' ratio to BHN MAX CYCLES=maximum cycles for S-N curve CYCLES=factor to scale cycles by	These factors are used to describe the S-N curve for the rail steel and will be adjusted for different rail metallurgies if the information is available. Use CYCLES factor as an additional adjustment for fatigue calibration.
18	CAL FOR WR	ABR, PLASTIC, BATTER	Used to adjust balance between abrasive wear and plastic flow. This information is not generally available but might be inferred from information on rail head area lost and rail head deformation. Adjustment for batter effect on CWR and jointed rail matching with rail wear data.
19	CAL FOR WEARMD	HI, LO, GF	Adjustment to wear on contact locations. These should be adjusted by comparison with actual wear data.
20	CAL FOR FATLIF	LIFE=fatigue calibration	This is a direct calibration of the fatigue life in years.

5. RMCM CALCULATIONS AND PRINTOUT OPTIONS

An eight-column space is allotted on the first line of the bulk data file for flags which can be used to select various calculation and printout options for the program.

Column one provides an echo-print of the input data. With a zero in this column, only the calibration file is printed -- exactly as it is stored on the left side of the page, and the numerical values picked out by the free format reader to be used in the program on the right side of the page (Appendix F.1). It is recommended, for the purpose of clarity and to avoid possible error, that a blank not be used as a substitute for zero in the specification of printout options. With a one in this column, a summary of the track parameters is printed, as well as a car-by-car summary of the vehicle parameters (Appendix F.2). When there is a two in column one, the program prints out the calibration file as well as a one-line summary of the parameters of each car (Appendix F.3).

Column two of the options code controls the car force and creep summary. With a zero in this column, the option is turned off. A one here provides a car-by-car summary of creep, batter and L/V ratios for each axle and contact position (Appendix F.4). A value of two gives a car-by-car summary of forces, batter, and L/V ratio for each axle and contact position (Appendix F.5). Three in column two results in a printout of both the creep and force summaries (Appendix F.6).

Column three controls the wear summary. With the column set at zero, the option is turned off. A one in the column provides a car-by-car summary of the wear rate, plastic flow rate, maximum stress, friction coefficient and Brinell Hardness by axle and contact position. It also examines the probability of false flanging and provides wear and batter summaries on a per-thousand-car, per-million-gross-tons, and per-year basis (Appendix F.7).

Column four controls the batter summary. With the column set at zero, the option is turned off. A one here provides a car-by-car summary of the batter rate for each axle and contact position (Appendix F.8).

Column five is used to control the fatigue calculations. A zero in the column turns the calculation off; a one turns it on.

Column six controls the engineering summary output. As with the other options, a zero in this column turns it off. A one in the column provides a summary of the overall total wear, batter, fatigue life, wear life and joint batter life for the traffic in the case (Appendix F.9). A two in the column gives a one-line summary of the high-rail wear and batter, low-rail wear and batter and gauge-face wear for all the traffic in the case. A label of the case run is also provided (Appendix F.10). A three in the column gives high-rail wear and batter, low-rail wear and batter and gauge-face wear for each car in the case (Appendix F.11). A four in the column provides a one-line summary of the wear, batter and fatigue lives for the case (Appendix F.12). A five in the column provides a one-line summary of the high-rail, low-rail and gauge-face wear rates for the case (Appendix F.13).

Column seven controls the costing calculations. Zero in the column turns it off and one turns it on. A sample of the cost summary is shown (Appendix F.14).

Column eight is available for future program expansion and is currently left blank. Table 5.1 summarizes the various options.

TABLE 5.1

PRINT OPTIONS

Column Number	Option Name	Option Number	Description
1	Input Echo	0	Echo print of input data off
		1	Echo print of input data on
		2	Summary of track and vehicle parameters
2	Car Summary	0	Car-by-car summary off
		1	Car-by-car summary of creep
		2	Car-by-car summary of the forces
		3	Car-by-car summary of both creep and forces
3	Wear Summary	0	Car-by-car summary off
		1	Car-by-car summary on
4	Batter Summary	0	Car-by-car summary off
		1	Car-by-car summary on
5	Fatigue Calculation	0	Fatigue calculations off
		1	Fatigue calculations on
6	Engineering Summary	0	Engineering summaries off
		1	Wear, batter and life summary for case
		2	One-line wear and batter summary for case
		3	Car-by-car wear and batter summary
		4	One-line life summary for case
		5	One-lihe wear summary for case
7	Costing Summary	0	Costing calculations off
		1	Costing calculations on
8		blank	For future expansion

6. PROGRAM SUBROUTINES

6.1 Subroutine ROOT

Subroutine ROOT is the main program for the rail wear computer model. It calls LOADER to load all the input data and then calls PASS1 to do the force, stress and rail deterioration estimations for each contact location. It next calls PASS2 to perform the deletion of traffic classes and the calculation of incremental and marginal costs and finally calls PRNT to print the results.

6.2 Subroutine LOADER

Subroutine LOADER calls the routines which handle the loading of data in a program run: subroutine BULK for the initial case, and subroutine SPOT for all succeeding cases. It calls the routines which scale the traffic data, if required, and includes the locomotive traffic classes. LOADER does some processing of the input data such as calculation of grade compensation of curves, balanced superelevation and work hardening effects. Also, subroutine LOADER prints out a summary of the parameters loaded for each case as requested (OUTPUT(1)=1 prints a detailed summary if input parameters; OUTPUT(1)=2 prints a compact summary of input parameters and calibration factors; OUTPUT(1)=0, no summary).

6.3 Subroutine BULK

BULK loads and error-checks the input data file for the first case in the run. Depending on the machine used, it assigns the logical units; that is, it assigns the name and type of the input, output, calibration, stress tables and scratch files. The format of the input data file and the definition of the input parameters which are loaded by subroutine BULK are given in detail in Section 3 of the report.

6.4 Subroutine CALS

CALS loads in the calibration file data into the program.

The calibration file is printed to the output file if all output flags (stored in array OUTP) are zero. This is provided as a debugging feature. If there is a problem in the calibration file, the routine is halted and the line number in the calibration file where the error has occurred is printed along with the message, 'ERROR IN CAL FILE'.

The stress tables must be created for the Rail Wear Cost Model to run. If a blank data file is read into the program as an input file, then subroutine CALS will initiate the building of the stress tables with a call to subroutine CONCEN. At the completion of this, the program will halt with the message, 'STRESS TABLES BUILT'.

A sample calibration file is shown in Appendix E. It shows the layout of the data set as well as gives typical values for the parameters. A table of the parameter names and descriptions is given below

TABLE 6.1

CALIBRATION FILE PARAMETERS

Card Number	Card Description	Parameter Name	Definiton of Parameter
1	Version number	VERSON	Version number for this program and calibration file
2	Material constants	E	Young's modulus for steel
		G	Bulk modulus for steel
		POIS	Poisson's ratio
3	Brinell Hardness Numbers	BHNX(1)	Brinell Hardness of hardened steel rails
		BHNX(2)	Brinell Hardness of hardened steel rails
4	Track constants	L	Track quality constant
		C	Hertzian contact deflection constant

5	Friction coefficients	PHIALL(1,1)	Maximum friction factor on high rail, unlubricated
		PHIALL(2,1)	Maximum friction factor on low rail, unlubricated
		PHIALL(3,1)	Maximum friction factor on gauge face, unlubricated
		PHIALL(4,1)	Limiting friction factor, unlubricated
6	Friction coefficients	PHIALL(1,2)	Maximum friction factor on high rail, lubricated
		PHIALL(2,2)	Maximum friction factor on low rail, lubricated
		PHIALL(3,2)	Maximum friction factor on gauge face, lubricated
		PHIALL(4,2)	Limiting friction factor, lubricated
7	Rail curvature assumptions in CNSTRS	CR(1)	High-rail radius of curvature
		CR(2)	Low-rail radius of curvature
		CR(3)	Gauge-face radius of curvature
		K	Constant setting occurrance of change in high-rail profile
		SUBT	Constant setting magnitude of change in high-rail profile
8	Wheel curvature assumptions in CNSTRS	CW(1)	High-rail wheel lateral curvature
		CW(2)	Low-rail wheel lateral curvature
		CW(3)	Flange wheel lateral curvature
		CW2FF	Wheel curvature with false flanging
9	Flange angle assumptions in CREEP	A	Radial distance down to flange contact
		FANGLE	Flange contact angle
		ADELTA	Change in A for CN profile
		FDELTA	Change in flange contact angle for CN profile
10	MMGT for marginals	XMARGN	MMGT upon which marginals are based
11	Calibration factors for LOADER	DELCUR	Curvature to reflect prehunting motion
		WORKHD(1,1)	Work hardening scale for high rail
		WORKHD(2,1)	Maximum curvature for high rail
		WORKHD(1,2)	Work hardening scale for low rail
		WORKHD(2,2)	Maximum curvature for low rail
		WORKHD(1,3)	Work hardening scale for gauge face
		WORKHD(2,3)	Maximum curvature for gauge face

12	Calibration factors for LOCO	CALOCO	Housepower scale factor
		LPC	Locomotives per consist
		SPD	Design speed
		EMPO	Empty-car axle loading
		DYNBRK	Dynamic braking force acting on car wheels
13	Calibration factors for ACTIVE	RUNOUT	Acceleration of car due to run-in/run-out
14	Calibration factors for XLOVRT	OFFBAL	Part of lateral force acting to increase L/V (0-.5)
		GWMIN	Minimum gauge-widening effect on L/V
		DBUFF(1)	Scale factor for buff-load effect on locomotives
		DBUFF(2)	Scale factor for buff-load effect on cars
15	Calibration factors for TRUCK	TRMSTF	Tramming stiffness
		TRMSLP	Tramming stiffness slope with car weight (theory = 0.0)
16	Calibration factors for REVCON	SDFAC(1)	Standard deviation of front-axle lateral force
		SDFAC(2)	Standard deviation of rear-axle lateral force
		SDFAC(3)	Standard deviation of middle-axle lateral force
		FCRITS	Critical lateral force for false flanging
17	Calibration factors for CYCRAT	SECAL	Endurance limit's ratio to BHN
		SUCAL	Ultimate stress ratio to BHN
		MCYCAL	Maximum cycles for S-N curve
		ONE	Contested level for bending moments
		CALCYL	Factor to scale cycles by
18	Calibration factors for WR	WRABR	Abrasive scale factor for wear
		WRPLS	Plastic scale factor for wear
		BATP2	P2 plastic scale factor for batter
		BATP1	P1 plastic scale factor for batter
19	Abrasive wear calibration for WEARMD	CALABR(1)	Calibration of abrasion on high rail
		CALABR(2)	Calibration of abrasion on low rail
		CALABR(3)	Calibration of abrasion for gauge face

20	Plastic flow calibration for WEARMD	CALPLF(1)	Calibration of plastic flow on high rail
		CALPLF(2)	Calibration of plastic flow on low rail
		CALPLF(3)	Calibration of plastic flow on gauge face
21	Threshold calibrations for WEARMD	SWCAL	Severe wear threshold calibration
		THRSCAL	Plastic flow threshold calibration
22	Calibration factors for FATLIF	CALFAT	Fatigue calibration
		MINER	Palmgren-Miner criterion
		IOFF	Depth to look for fatigue

6.5 Subroutine CONCEN

Subroutine CONCEN builds a table of maximum and minimum stresses for a range of wheel/rail contact friction coefficients and for a range of depths into the rail.

An elliptical distribution of normal and tangential forces is assumed at the contact location.

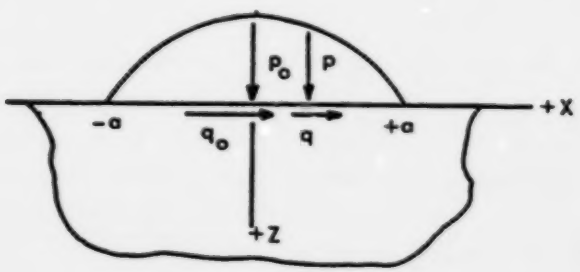


Figure 6.1 Distribution of forces at contact location

For the purpose of simplicity, the table is calculated for a unit contact patch radius for a unit maximum contact stress. The stresses are scaled with changes in maximum contact stress, and the level to which these stresses are applied are scaled inversely with the radius of the major axis of the contact patch, for the estimation of stress concentrations in CYCRAT.

The scaling of the depth to which stresses are applied causes a slight error, as can be seen by looking at the equations, but saves substantially on computer processing time and does not have a large effect on the overall fatigue life estimation. The calculation is done one time instead of repeatedly for each level into the rail, for each contact location, for each friction value, for each car type and for the total annual traffic.

The stresses due to an elliptical distribution[1] of the normal load are:

$$\sigma_{xn} = -\frac{P_0}{\pi} z \left[\frac{a^2 + 2x^2 + 2z^2}{a}\bar{\psi} - \frac{2\pi}{} - 2x\psi\right]$$

and the stresses due to an elliptical distribution of tangential forces are:

$$\sigma_{xt} = \frac{q_o}{\pi} \left[2x^2 - 2a^2 - 3z^2)\psi + 2 \quad \frac{x}{a} + 2\,(a^2 - x^2 - z^2)\,\frac{x}{a}\bar{\psi}\right]$$

where: a = the half width along the contact area

x = distance away from the centre of the contact patch along the rail

z = distance into the rail from the surface contact

p_o = maximum normal contact stress

q_o = maximum tangential stress

and where ψ and $\bar{\psi}$ are functions of a, - and z.

---

1 J.O. Smith and Chang Keng Liu, "Stresses due to Tangential and Normal Loads on an Elastic Solid with Application to Some Contact Stress Problems," Journal of Applied Mechanics, June 1953.

$$\psi = \frac{\pi}{k_1} \frac{1 - \sqrt{\frac{k_2}{k_1}}}{\sqrt{\frac{k_2}{k_1}} \sqrt{2 \sqrt{\frac{k_2}{k_1} + \left(\frac{k_1 + k_2 - 4a^2}{k_1}\right)}}}$$

and

$$\bar{\psi} = \frac{\pi}{k_1} \frac{1 + \sqrt{\frac{k_2}{k_1}}}{\sqrt{\frac{k_2}{k_1}} \sqrt{2 \sqrt{\frac{k_2}{k_1} + \left(\frac{k_1 + k_2 - 4a^2}{k_1}\right)}}}$$

$$k_1 = (a + x)^2 + z^2$$

$$k_2 = (a - x)^2 + z^2$$

According to Mindlin,[2] $q_o = fp_o$, where f denotes the coefficient of friction of the surfaces of contact. Thus, the stresses due to combined application of normal and tangential loads become:

$$\sigma_x = \sigma_{xn} + f\sigma_{xt}$$

In the routine, the stresses for a level z and friction coefficient f are calcualted for a range of x values. The maximum stress found over the values of x is placed in the maximum stress table, called RESULT. The minimum stress is placed in the minimum stress table, RESUL2. These tables are used in the estimation of cycle ratios in subroutine CYCRAT.

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2 R.D. Mindlin, "Compliance of Elastic Bodies in Contact," Journal of Applied Mechanics, Trans. ASME, Vol. 71, 1949.

6.6 Subroutine SPOT

SPOT loads and error-checks spot-data from the input data file. It also contains the program exit.

Spot-data are used to describe the case conditions for the second, third or succeeding cases in a run. Track, maintenance and cost parameters can be entered and varied through SPOT, but the traffic mix must remain the same as that entered for the initial case through subroutine BULK.

The variables which can be entered through SPOT are:

TOTMGT	the annual total million gross tons traffic
DCURV	track curvature in degrees
SE	superelevation in inches
GRAD	grade in per cent
IRAIL	CWR/jointed and BHN flag
RI	cross-section inertia of rail
U	track modulus
TRV	maximum vertical irregularity
TRL	maximum lateral irregularity
DIP	dip joint angle
RO	dip joint support factor
MR	mass of the rail
MT	mass of the ties
GWG	gauge widening
LUBRIC	lubrication flag
TWA	transposal wear allowance
ROK	return on investment
DELTC	rail escalator
UCOST	replacement cost/mile
SALV	salvage value/mile
BHN	Brinell Hardness Number of rail steel
JOINTED	sets value for CWR flag, ICWR = 0
CWR	sets value for CWR flag, ICWR = 1
L	track quality constant
C	Hertzian contact deflection constant
V	speed of traffic in miles per hour

All spot-data are of the form (variable name) = (value); for example, TOTMGT = 20.0, except for JOINTED and CWR which are character strings that just have to appear in the spot-data section for the value of ICWR to be set.

6.7 Subroutine SCLMGT (TOT)

Subroutine SCLMGT rescales the annual million gross tons of each car class in the traffic mix. The action taken in the subprogram is determined by the value of TOTMGT read into the routine. If TOTMGT is negative, the annual MMGT's of the car classes are scaled so that their total, not including annual MMGT's of locomotives, equals TOTMGT. If TOTMGT is positive, the annual MMGT's of the car classes, including locomotives, are scaled so that their total equals TOTMGT.

6.8 Subroutine TRAIN (IWAS)

Subroutine TRAIN sums the rolling resistance of the trailing consist, determines the number of locomotives, if necessary, and determines if braking is required. It is performed once for each traffic mix.

If there are no locomotives specified in the traffic mix, then the total power requirements, and hence the number of locomotives, are calculated as determined by the worst extended grade on the route. The variable WPR, card four in the data file, is used to read in the worst extended per cent grade by direction for this situation. The parameter IWAS equals 1.

If there are locomotives specified in the traffic mix but the annual million gross tons of locomotives are not, then IWAS equals 2 and WPR is used to read in the number of cars per locomotive by direction and thus to calculate the MMGT's of the locomotive classes.

If the locomotives are included in the traffic mix specification and the MMGT's of the locomotive classes are present, then WPR is the weight-to-power ratio (tons/hp) of an average consist by direction and IWAS equals 3.

Rolling resistance is calculated and summed for the cars and locomotives. A modified form of the formula for train resistance derived by Davis[3] is used:

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3 Davis, W.J., "The Tractive Resistance of Electric Locomotives and Cars," General Electric Review, October 1926.

$$R = a + \frac{b}{(W/n)} + CV + \frac{dAV^2}{W}$$

where: R = specific resistance (force per unit weight)

W = car weight

A = cross-sectional area of the car

n = number of axles

V = speed

a,b,c,d = empirical coefficients.

The values used in the model are a = 0.6, b = 20, and c = 0.01. These coefficients, known as the Modified Davis Formula, resulted from post-war tests conducted by Canadian National. They have been widely accepted by North American railways and have been incorporated into recent AAR- and FRA-sponsored train simulation programs. It is noted that higher values for these coefficients have been proposed. The AREA-recommended value for aerodynamic drag coefficient has been used, dA = 0.07.

Changes in elevation of the track introduce a longitudinal component into the acceleration of gravity. The longitudinal component is equal to the change in elevation for a unit distance travelled (i.e. track gradient):

$$\frac{\Delta y}{\Delta L}$$

as illustrated in Figure 6.2.

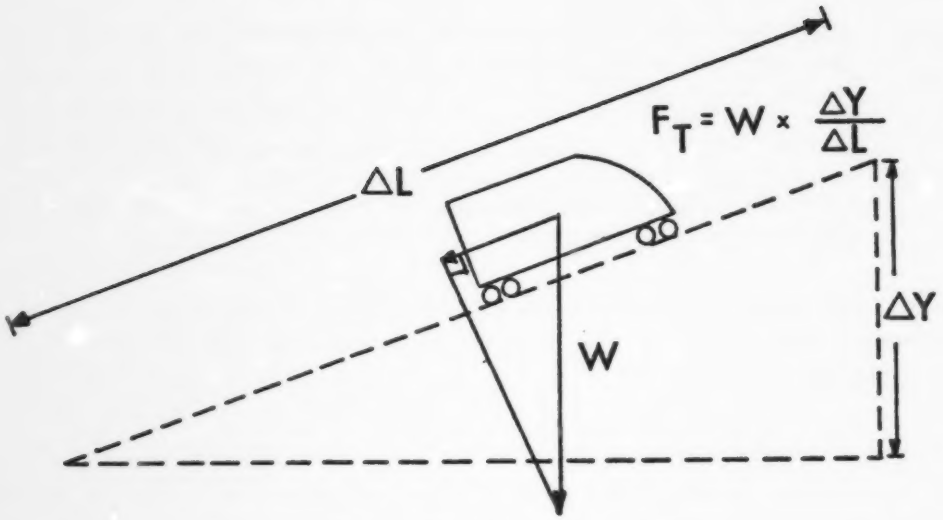

Figure 6.2 Illustration of resistance force due to track gradient

The resistance due to grade is therefore expressed as:

$$R_G = 20. \times GRAD$$

where: R_G = resistance (lb/ton)

GRAD = track gradient in per cent

For the estimation of the incremental resistance associated with curve negotiation, a resistance of 0.8 lb/ton per degree of curvature is used. This is a crude value based on tests conducted by the Pennsylvannia Railroad in 1915. Increased curve resistance can be attributed to:[4]

- higher wheel flange contact forces set up by frictional imbalance in the misaligned wheel set, unbalanced superelevation and truck swivel resistance

4 G.W. English et al., Railway Linehaul Energy Intensity: An Analysis Leading to Design of a Train Simulation Software Package, CIGGT Report No. 80-15.

- additional journal resistance for plain journal bearings due to misalignment of the axle relative to the truck centre-line

- lateral and longitudinal sliding due to wheel set misalignment and lack of compensation for different wheel paths through rolling radii differences respectively.

These are not considered worth including for the estimation of motive requirements but appear in the detailed wear estimation in other parts of the program.

A slightly different formula is used to calculate the resistance for the locomotives. It is based upon a recent study by DeLCan[5] reviewing CN's and CP's development of the TPC for fuel-use modelling. CN's recalibrated formula is used:

$$R = 1.5 + 18\ N/W + .03\ V + k\ CA\ V2 \times 10\text{-}4/W$$

where: R = specific resistance in lbs/ton

N = number of axles of the locomotive

W = weight in tons

A = cross-sectional area in square feet

C = air resistance coefficient depending on car type

k = wind factor

V = speed in miles per hour.

Locomotives of 186 tons with six axles are assumed for the resistance estimate and an aerodynamic drag coefficient of 1.4992 assuming 1 in 4 locomotives is used.

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5 A Comparison of Modal Energy Consumption in Intercity Freight: Phase I/Study Feasibility, DeLCan (DeLeuw Cather Canada Ltd) for Transport Canada, April 1979.

Where braking is required and the force of the cars on the locomotives is not too large, dynamic braking is assumed. A curve fit for the standard dynamic brake force envelope for an SD-406 locomotive is used and buff loads are calculated.

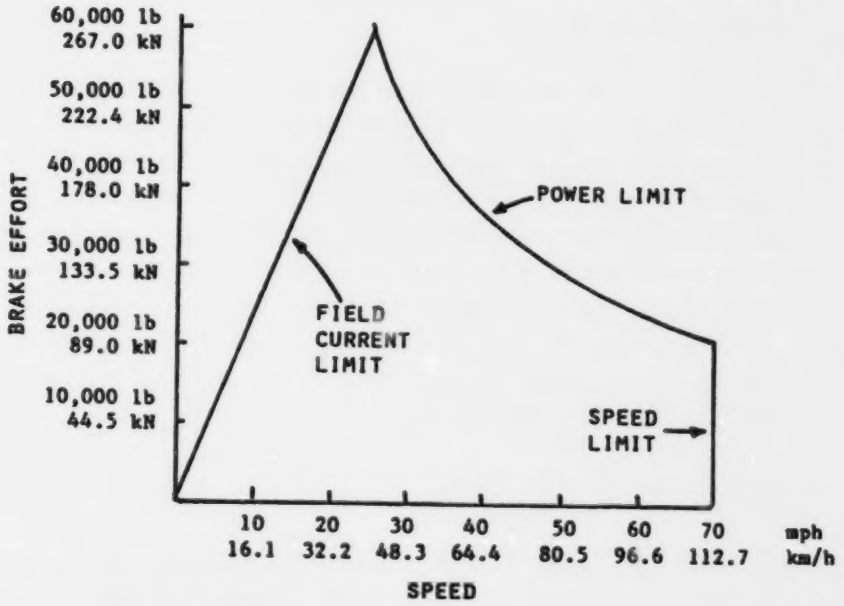

Figure 6.3 Standard dynamic brake force envelope - SD-40

Where dynamic brakes are not enough to resist the force of cars, air brakes are assumed. A scale factor is used to estimate the effect of air brakes. Both cars and locomotives resist. Buff loads are assumed to be zero.

6.9 Subroutine LOCO (N, PW, GRD)

Subroutine LOCO adds a six-axle, 186-ton locomotive class to the car data at location N in the traffic mix data, determined in subroutine TRAIN.

The annual million gross tons of locomotives is calculated based on the assumption of 3000 hp SD-40's and on the values for design grade,

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6 English et al., op. cit.

GRD, and the total annual locomotive power requirements, PW, determined by the total rolling resistance of cars and locomotives which must be overcome. The power required per locomotive to overcome its own rolling resistance is calculated on the assumption that a reasonable friction coefficient must be obtained on the design grade (i.e. 0.18 friction coefficient at 7 miles/hour).

6.10 Subroutine LINE (IN)

Subroutine LINE is a simple subprogram which keeps a record of the number of lines which have been printed on an output page. LINE is called before a write to the printer file with the parameter IN set. IN is the number of lines to be printed. If IN is negative, a new page is initiated with the run identification and the date printed at the top. If IN is zero, nothing is done except a return to the subroutine call. If IN is positive, its value is added to the line count. If the line count is less than 49, then a return to the subroutine is performed. When the line count reaches 49, a new page is started with the header at the top and the line count is reset to zero.

6.11 Subroutine FREEIN (INPUT)

Subroutine FREEIN is a free format reader. It is used to load the input data information into subroutines BULK and SPOT and to load the calibration information into subroutine CALS. INPUT is the input file number. The use of FREEIN eliminates the necessity for adherence to strict format in the data files and requires only the separation of numbers by commas. Integer, floating point and exponential values are accepted by the routine and converted to floating point numbers. FREEIN also accepts alphabetic information. It stores the first six characters of each word preceding a numeric value or delimiter which can then be linked to the numeric value outside the subroutine.

Subroutine FREEIN reads 80 character records from the data file and stores the information in array ALPHA. The floating-point equivalents of the numbers which have been found are stored in array WORD. A count of the resulting floating-point numbers in array WORD is stored in NWRD. The array VARS contains the alphabetic variable names preceding each value. For example, reading from input ALPHA contains:

LOAD ALPHA=1.34,N=1,C=4+12,SOME CHARACTERS,12.5

After being processed by subroutine FREEIN, WORD contains:

1.34,1.,4.E12,12.5

in internal floating point; VARS contains

```
'A','L','P','H','A',' ',
'B',' ',' ',' ',' ',' ',
'C',' ',' ',' ',' ',' ',
'C','H','A','R','A','C'
```

in every other character; and NWRD=4.

6.12 Subroutine PASS1

Subroutine PASS1 calls the routines associated with the estimation of forces, slips and associated deformations at each of the contact locations. It takes the information loaded and processed by the input section controlled by subroutine LOADER and passes it on to subroutines VEHIN, CAR, WR and LIFE. The subroutines will print wear- and batter-rate summaries and life summaries for each car type in each direction unless none of the engineering summaries are specified, i.e. OUTP(1), OUTP(2), OUTP(3) and OUTP(4) all equal zero.

6.13 Subroutine VEHIN

Subroutine VEHIN extracts car information for a specific car class from the data storage area containing the information for all car classes, to be used in calculation of the car type's contribution to rail wear. It prints a summary of the car information unless none of the engineering summaries are selected, i.e. OUPT(1), OUTP(2), OUTP(3) and OUTP(4) all equal zero. A compressed summary is printed if OUTP(1)=2.

6.14 Subroutine CAR

Subroutine CAR calls the routines which calculate contact patch slip rates, friction factors, high- and low-frequency dynamic loads, high-

and low-frequency batter loads, slip vector angles and the probability of false flanging on the low rail. For each car it stores this information according to axle and wheel/rail contact location. If OUTP(2)=1, it prints a slip summary for each car; if OUTP(2)=2, it prints a force summary for each car; if OUTP(2)=3, it prints both a slip and a force summary; and if OUTP(2)=0, no summary is printed.

6.15 Subroutine ACTIVE

Subroutine ACTIVE computes the coupler load at the locomotive (in buff only), and the torque at each axle, TORQ. Cars are treated separately from locomotives. One of three conditions is considered for each type: the locomotive is pulling the consist (IAM(I)=1), there is dynamic braking and thus only the locomotive is braking (IAM(I)=2), or the air brakes are activated and all cars are braking (IAM(I)=3). The forces on the locomotive classes and car classes calculated in subroutine TRAIN are used in the calculation of the torque at each axle. A dynamic run-in/run-out acceleration is assumed for the calibration of torque on the car axles in the situation where the locomotive is pulling the consist.

6.16 Subroutine VERT

Subroutine VERT calculates the vertical and lateral car loads on the rail normal to a line drawn between the rail heads. It considers the car speed, the track curvature, superelevation of the curve and height of the car centre of mass in the calculation and distribution of forces.

The lateral force due to the car travelling around the curve is:

$$F_c = \frac{MV^2}{r}$$

which becomes:

$$F_c = \frac{MV^2 \cdot 2 \cdot \sin\left(\frac{1}{2} \cdot \frac{\pi}{180} \cdot D\right)}{30.48}$$

where: M = mass of the car (kg)

V = speed of car (metres/second)

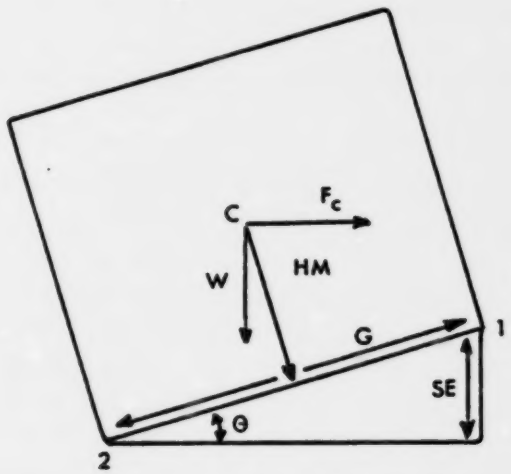
D = track curvature (degrees)

and $30.48 = 2 \cdot r \cdot \sin \frac{0}{2}$ for track curvature

r = radius of curve (metres)

0 = track curvature (radians).

For determining the appropriate forces parallel and normal to the plane of the rail heads, a vector diagram is useful, as illustrated in Figure 6.4 (note that the vectors shown are not to scale).



G = gauge of track
1 = top of high-rail head
2 = top of low-rail head
SE = superelevation
0 = track angle from horizontal due to superelevation (0 is small)
C = car centre of mass
HM = height of car centre of mass
F_c = lateral force due to curving
W = vertical force due to car weight

Figure 6.4 Force diagram for rail car on curve

Total lateral force along plane of rail heads is

$$F_{lat} = F_c \cos \theta - W \sin \theta$$

Total normal force to plane of rail heads at high rail is:

$$Fl_{norm} = \frac{1}{2} (F_c \sin \theta + W \cos \theta) + \frac{HM}{G} (F_{lat})$$

Total normal force to plane of rail heads at low rail is:

$$F2_{norm} = \frac{1}{2} (F_c \sin \theta + W \cos \theta) - \frac{HM}{G} (F_{lat})$$

6.17 Subroutine XLOVRT

Subroutine XLOVRT computes the vertical force with consideration of torque on the wheels, it calculates the effect of gauge-widening on L/V, the L/V itself, and off-loading due to traction in locomotive axles.

As a rail vehicle enters a curve, lateral forces are generated at the various wheel/rail contact areas. The forces are due to complex interactions between the track, truck, axles and body of the car. Comprehensive computer programs have been developed to model the detailed interactions during curve negotiation but these are very time-consuming. In the Rail Wear Cost Model, some simplifying assumptions have been made which, it is felt, provide a reasonable approximation.

The L/V ratio is actually a continuously varying quantity. As a truck negotiates a curve, the L/V ratio will vary considerably, depending on the situation. In subroutine XLOVRT it was assumed that curving could be modelled as a steady-state phenomenon with L/V as a constant for a given curve and truck type. It was therefore decided to use the RMS value of the measured L/V signatures from different vehicle types as an indicator for the steady-state value. Figure 6.5[7] shows L/V versus curvature for various car types travelling at balanced speed around curves.

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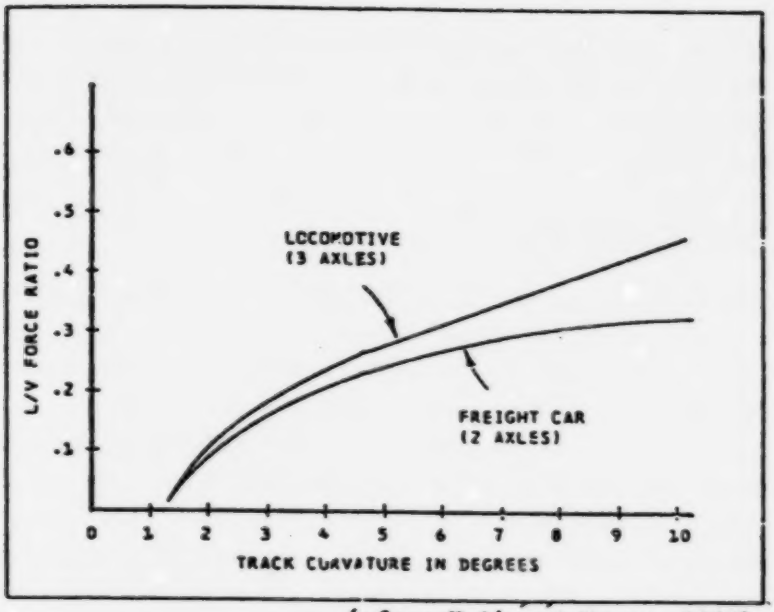
7 Air Brake Association, Modern Freight Car Handling, 1967. L.F. Koci and H.A. Marta, "Lateral Loading Between Locomotive Truck Wheels and Rail Due to Curve Negotiation," ASME, 625.062, A512. 65-WA/RR4.



(after Koli and Marta, 1967)

Figure 6.5 L/V force ratio versus track curvature

Subroutine XLOVRT was designed to give reasonable estimates for lateral/vertical load ratios. It fulfills this purpose by using a series of empirical equations based on test measurements.

The calculations are broken into three categories: freight cars, locomotives and passenger cars. Separate equations exist to calculate the L/V ratios for freight cars and locomotives. Passenger cars have rigid bogies which tend to exhibit a greater flexibility than those of the locomotive. As an approximation to the L/V for passenger cars, the L/V is set to the average of the values calculated for freight cars and locomotives. This is an over-simplification which should be modified as new data becomes available.

The empirical equations are based on balanced superelevation curving data. Changes are made within the subroutine to compensate for centrifugal forces due to unbalanced superelevation. Increments to the L/V due to buff-type loading, gauge-widening and gradient effects are also calculated within the subroutine. Each axle of the truck is assigned a value of L/V. Leading axles use the results from XLOVRT, trailing axles are assigned an L/V value of 0.0 and intermediate axles are given the average of the two.

After the values have been assigned to the different axles, the L/V ratio will be used to calculate normal loads at the three contact locations on each axle. These calculations are primarily carried out in subroutine CREEP.

6.18 Subroutine DELTA

Subroutine DELTA looks up the angle of attack for locomotives. As a railway car enters a curve, it is forced to follow the circular path traced out by the rail but the natural tendency of a car, because of its momentum and truck design, is to follow a straight course. This results in an impact or series of impacts between the wheel and rail at an angle termed the angle of attack or misalignment. The repeated impacts between the wheels and rails on curves over time result in the abrasive removal of substantially greater amounts of steel than is worn off on tangent track. The expected amount of wear increases as the degree of curvature and angle of attack gets larger.

Like the L/V ratio, the angle of misalignment (DEL) is constantly changing. The RMS value of the variable DEL is used as an estimate of a 'steady state angle of misalignment'. DELTA was constructed to produce reasonable estimates of the angle of misalignment which would then be used (after calibration) to estimate rates of slip at the rail/wheel interface.

Subroutine DELTA is a collection of empirical equations based on measurements taken from freight cars and locomotives curving under balanced conditions. Figure 6.6[8] presents the steady-state values for the angle of misalignment versus degree of curvature for the different vehicle types.

As with the L/V ratio, DEL for passenger cars is approximated by taking the average value of DEL as calculated for freight cars and locomotives. The leading axle of each bogie is assigned the calculated value of DELTA, trailing axles have DELTA=0, and intermediate axles are assigned interpolated values.

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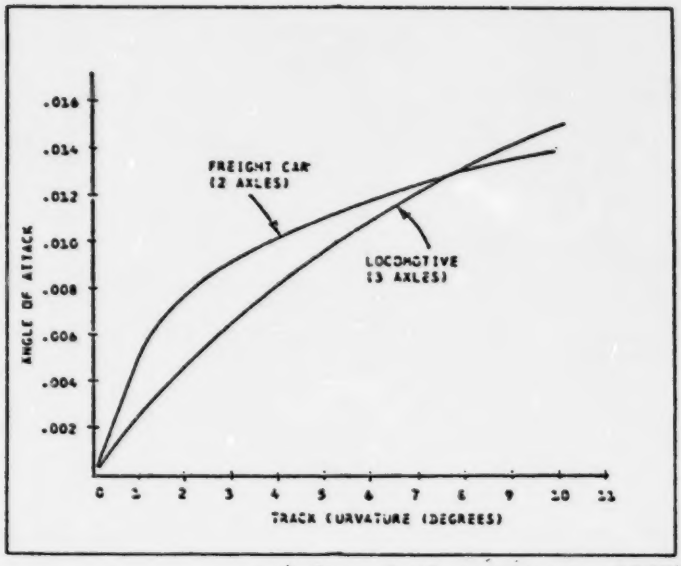
8 Ibid.



(after Koli and Marta, 1967)

Figure 6.6 Angle of attack versus track curvature

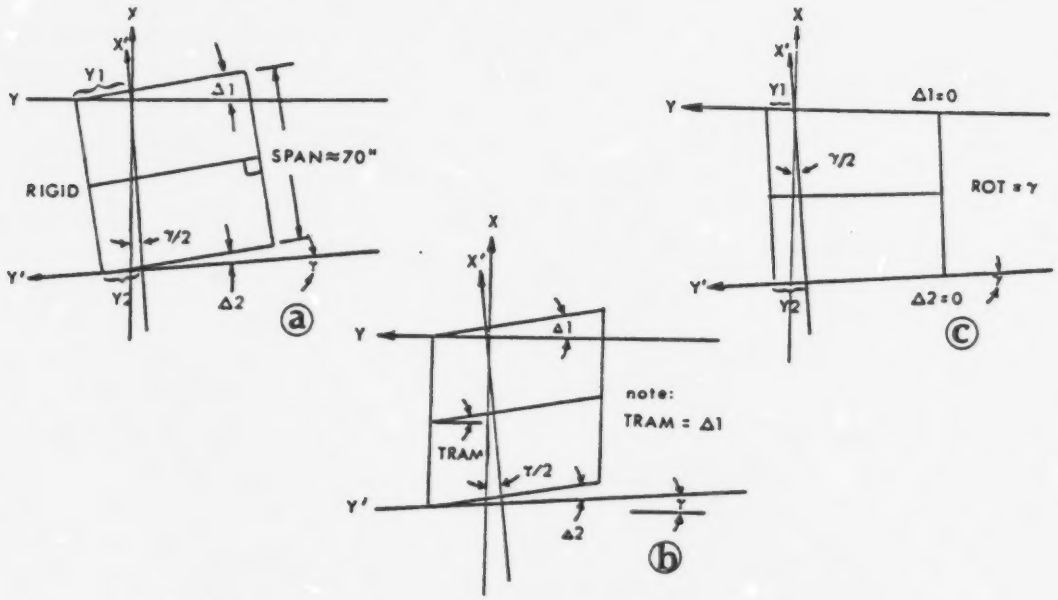
The angle of attack is an important parameter in the prediction of rail wear. Lateral sliding is a direct result of the angle of attack and is the chief cause of abrasive rail wear in curves.

6.19 Subroutine TRUCK

Subroutine TRUCK imposes geometry considerations across linking axles before subroutine CREEP computes the slip vectors. It also imposes a flange-free curving region on the truck.

The geometry constraints developed are applicable to tramming, steering and rigid truck types. By adjusting tramming, rotational and rear-axle position stiffness in the routine, the behaviour of different trucks can be represented. The tramming stiffness and its variation with wheel load are loaded through the calibration file.

A simple rigid truck is shown in Figure 6.7(a), a simple tramming truck is shown in Figure 6.7(b), and a simple steering truck is shown in Figure 6.7(c). Using these diagrams as a guide and the variables as defined, the geometry for these cases is as follows:



Definition:

- Y1 = distance to leading outer wheel (X, Y coordinate system)
- Y2 = distance to trailing outer wheel (X', Y' coordinate system)
- Δ1 = angle of attack of leading axle (X, Y coordinate system)
- Δ2 = angle of attack of trailing axle (X', Y' coordinate system)
- X,Y = leading-axle coordinate system
- X',Y' = trailing-axle coordinate system
- = angle between X, Y Δ X', Y' coordinate system

Figure 6.7 Geometric representation of (a) rigid truck, (b) tramming truck, and (c) steering truck

For a rigid truck:

$$\Delta 2 = \Delta 1 - \gamma$$

$$Y2 = Y1 - SPAN \cdot (\Delta 1 - \gamma/2)$$

where:

$$\gamma = \frac{\text{distance between axles of truck}}{\text{radius of curve}} = \frac{SPAN}{r}, \ \gamma \text{ is a small angle}$$

For a tramming truck:

$$\Delta 2 = \Delta 1 - \gamma$$

$$Y2 = Y1 - SPAN \cdot (\Delta 1 - \gamma/2) + SPAN \cdot TRAM$$

And for a steering truck:

$$\Delta 2 = \Delta 1 - \gamma + ROT$$

$$Y2 = Y1 - SPAN \cdot (\Delta 1 - \gamma/2 - TRAM + ROT/2)$$

Finally, if some lateral travel of the rear axle is allowed, the equations become:

$$\Delta 2 = 1 - \gamma + ROT$$

$$Y2 = Y1 - SPAN \cdot (\Delta 1 - \gamma/2 - TRAM + ROT/2) + X$$

TRAM, ROT and X are freedoms introduced to describe the tramming cycle, the rotational cycle and distance of the rear axle from centre for the tramming, steering and rigid trucks. A standard truck is a tramming truck.

The inter-axle ties are modelled as simple springs. Therefore:

$$TRAM = (L1-L2)/(TSTIFF \cdot SPAN)$$

$$X = (L1-L2)/XSTIFF$$

where: L1 = lateral force on the front axle

L2 = lateral force on the rear axle

TSTIFF = tramming stiffness

XSTIFF = rear axle position stiffness.

The rotation component has been idealized when used with ROT = γ.

6.20 Subroutine CREEP

Subroutine CREEP estimates slip coefficients and generates creep forces and normal forces for an axle. It enforces the torsional moment balance for the axle, and if the flange has been reached, it enforces the L/V and the sum of vertical forces at the high rail.

During the negotiation of a curve by a rail vehicle, lateral forces are generated by friction between the wheels and the rail. These friction forces are closely related to rates of slip at each of the contacts. As with the angle of misalignment and L/V ratio, the rates of slip vary due to dynamic interactions between the vehicle and the track. In subroutine CREEP, the calculation procedure is simplified by the assumption that curving can be modelled as a steady-state phenomenon, with fixed L/V, angle of attack and creep rates.

In the prediction of creep rates, several important functional relationships exist which must be modelled mathematically, the most important of these relationships being the interaction between friction and creep. Figure 6.8 shows friction versus creep curves for different rail surface treatments.

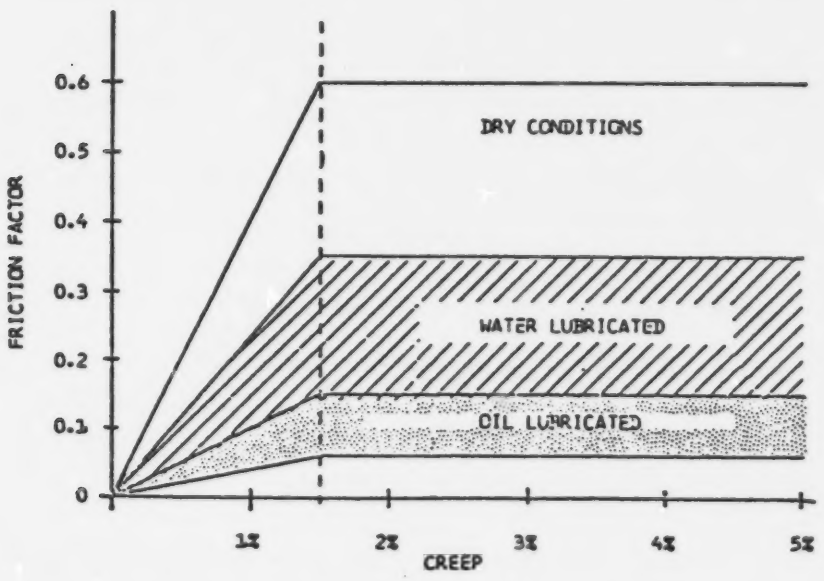


Figure 6.8 Friction factor versus creep coefficient

In the analysis, each axle is considered separately. A torque balance is performed to determine the required forces and friction factors to be generated at each of the contact patches. Three zones of contact can exist on each axle: high-rail head, low-rail head and gauge face.

At each contact location there exists a relative velocity between it and the rail surface. The friction factors at each of the contacts are calculated as a function of the rate of slip and, in the limiting case of gross slip (sliding), the maximum friction factor is determined by the lubrication conditions. The calculation procedure is iterative and involves assigning an initial longitudinal slip at the high-rail head. Taking into account the effects of path length difference, an appropriate slip is calculated for the low rail. Lateral creep due to the angle of misalignment is added vectorally to the longitudinal creep at the two rail heads. Subroutine GUESSO is used to estimate a new value of longitudinal creep at the high-rail head.

The gauge-face rate of slip has a more complex calculation procedure which is due to the fact that in curves the gauge-face contact patch leads that of the rail head and the slip that occurs is usually gross sliding, therefore generating the limiting friction factor. Not only does the gauge-face slip have lateral and longitudinal components, but because of the inclined structure of the flange surface, a vertical component also exists. The vertical flange force component causes off-loading at the leading outer wheel. In high curvature areas this off-loading becomes a large proportion of the wheel load and it is thus a major cause of wheel climb.

The slips at the various contacts are then converted to friction factors using the measured data. These friction factors are employed in the calculation of torques generated at the contacts, which are then summed along with any traction or braking torques in the axle. If the sum is zero, the conditions are met; if not, a new longitudinal slip at the high-rail head is assigned and the calculation procedure repeats.

Rates of slip or sliding at the three contact locations, friction factors for each location, and the final normal loads at the contacts after any off-loading has been taken into account, are calculated. These parameters are used to determine dynamic loads, abrasive rates of

wear, threshold stress for plastic flow and numerous other important quantities.

In this analysis, each axle is considered independently for the computation and summation of torques. Inter-axle forces that are transmitted through the structure of the car have been taken into account in the calculations of the lateral/vertical force ratio and in the evaluation of the angle of misalignment. Since steady-state performance is assumed, forces due to rotation of the axles are ignored, and only those rolling forces that affect the rail through its direct contact with the wheels are considered.

Subroutine CREEP was designed for 'average' conditions; it accepts the wheel loads from the input data file and limiting friction factors from the calibration file, along with the L/V and the angle of attack. The only quantities that need attention are the friction factors. Differing rail surface treatments dictate differ limiting friction factors.

6.21 Subroutine GUESSO

Subroutine GUESSO is used in the iterative procedure to obtain a torque balance in subroutine CREEP. It is a simple routine to perform a linear interpolation with the estimated longitudinal slip on the high-rail head, LONSL1, as the x-value, the independent variable, and with the resulting sum of the torques for the axle, SUM, as the y-value, the dependent variable. For torque balance, the sum of the torques must be zero (actually, if the sum of the torque is less than 0.3 and the longitudinal sliding is less than 0.2, torque balance is assumed).

The routine uses the present values of LONSL1 and SUM and the previous values of LONSL1 and SUM to estimate the value of LONSL1 for which SUM is zero.

6.22 Subroutine VDYN

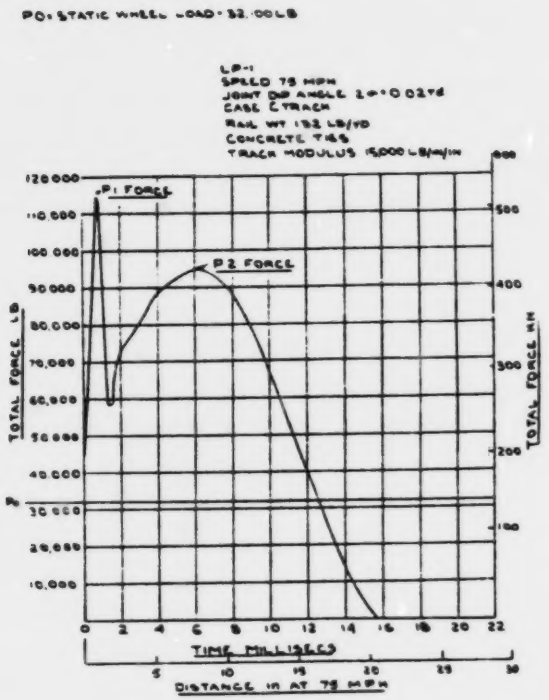
Subroutine VDYN computes high- and low-frequency dynamic friction and batter loads.

Dynamic increments to static wheel loads result from the inability of the wheels to smoothly follow the rail. Irregularities such as joints, soft spots, wheel flats, surface roughness, rail corrugation, and many others, make smooth continuous contact impossible.

The dynamic forces generated are a function of track and vehicle parameters, the most important of these parameters being train speed, gross car weight, unsprung weight, track stiffness, track weight, size of irregularities and shape of irregularities. In subroutine VDYN, the static wheel load is converted into dynamic loads in two different load environments: joint or weld locations, and continuous surface irregularities.

Two dynamic forces are encountered at rail joints. The first, usually labelled P1, is an impact force of high frequency; second, P2, is a rebound force of lower frequency. The high-frequency (500-1000 Hz) P1 force is thought to be the major cause of rail batter, but has no effect on the ballast because of its high-frequency nature. The P1 force is dependent on speed, the joint dip angle, wheel load and track weight. The dynamic increment is not affected by track stiffness or unsprung weight. The P2 force, on the other hand, is of low frequency (20-200 Hz) and occurs further along from the joint (10 inches). The lower-frequency load is absorbed by the track structure and, as a result, the track structure will be degraded, potentially producing a soft spot. The magnitude of the P1 force is larger than that of the P2 dynamic force, and the difference between the two increases with speed. The P2 force varies with changes to the unsprung weight and track stiffness. In the case of continuous-welded rail, a calibrated P2 force is used as an estimate for the dynamic loading resulting from a dip angle at the weld locations. Typical P1 and P2 force signatures are shown in Figure 6.9 for a high-speed case.

Another dynamic load environment exists which can generate loads in various frequency ranges. These loads are caused by rail surface irregularities, and it is thought that these resonance forces are the major cause of rail corrugations. Two specific frequency ranges are considered in VDYN and they include a high-frequency load due to surface roughness, and a lower-frequency load due to longer wavelength (inches to feet) surface irregularities.



(after Nayak, 1973)

Figure 6.9 Typical force/time history at dipped rail joint

The high-frequency load (100 Hz) is a case where the forcing frequency is much higher than the natural resonance of track structure. The resulting dynamic force is normally distributed around the static wheel load, P_o, with the mean being equal to P_o. As an estimate of the high-frequency load, a single standard deviation of the dynamic increment is used. The resulting contact stress is then calculated using the P_o plus the standard deviation. The high-frequency load (PHF) is dependent on the gross weight of the vehicle; the unsprung weight is of little importance. As with the Pl batter force, the high-frequency component does not have a great effect on the track structure. It is therefore only considered when dealing with rail and wheel wear.

Another important dynamic load resulting from rail irregularities exists at much lower frequencies. This low-frequency (30 Hz) dynamic load (PLF) is caused by longer wavelength irregularities in the order of a few inches to several feet. This PLF load is similar to the P2 batter force in that it is dependent on the unsprung mass of the car and the track mass. Since the lower frequency is absorbed by the track structure, it is thought that it has direct effects on the ballast degradation.

Two curves are used to characterize the high and low dynamic increment to the static load which are based on work presented by Nayak.[9] They are as follows:

$$LI_{HF} = k \cdot (C \cdot P_N)^{0.08} \cdot \left[\frac{17.6\ V}{\sqrt{U/MR}}\right]^{1.44} \cdot \left[\sqrt[4]{\frac{E \times I \times \sqrt{u}^{0.75}}{(L)^{0.48}}}\right]^{0.84}$$

where: k = constant depending on units

P_N = normal level at contact point

V = vehicle speed

u = track modulus

MR = mass of rail per unit length

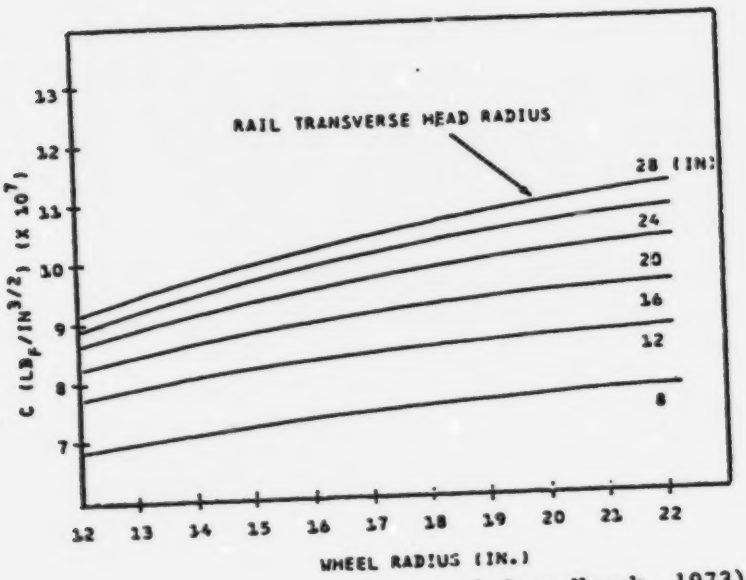
E = Young's modulus for steel

I = rail cross-section inertia

C = Hertzian contact deflection constant, see Figure 6.10, 8.3×10^7 for 18" wheel, 12" transverse rail head radius

L = constant which determines the shape of the normal distribution around the static load ($L = 5 \times 10^5$ for poor track, $L = 5 \times 10^6$ for average track, $L = 5 \times 10^7$ for good track)

9 P.R. Nayak, "Contact Vibration of a Wheel on a Rail," Journal of Sound and Vibration, January 1973, pp. 277-293.



(after Nayak, 1973)

Figure 6.10 Hertzian contact deflection constant versus wheel radius and rail transverse head radius

$$LI_{LP} = K \cdot (TRV)^{0.72} \cdot V \cdot \left[\frac{\sqrt[4]{E \times I \times u^{0.75}}}{(MR + MT)} \right]^{0.5} \cdot (W_u)^{0.33} \cdot P_N$$

where: K = constant depending on units

MT = mass of ties per unit length

W_u = vehicle unsprung weight per wheel

Calculations of contact rolling stresses use the larger of the two contact resonance forces caused by continuous surface irregularities. P1 and P2 type forces are considered at joints or welds to estimate batter damage, specifically plastic flow.

6.23 Subroutine REVCON

This subroutine calculates the probability of an occurrence of false flange contact at the inner wheels of a curving truck.

As the vehicle negotiates a curve, lateral forces are generated which must be balanced by the track structure. For heavy vehicles and high degrees of curvature, lateral forces may be of sufficient magnitude to cause substantial gauge widening, and it is in these cases that false flange contact is likely to occur.

REVCON assumes that when the lateral forces exceed an initial value, sufficient gauge widening exists for false flange contact to occur. The probability of an occurrence is calculated as a function of the difference between the lateral force and the critical force.

The critical force can be varied, depending on the track type. Presently the critical force is based on 132 lb/yd rail with wooden ties. The value of the limiting force is corrected for different rail inertias but not for different tie types. If concrete ties are to be modelled, the critical force should be increased.

The calculation procedure is based on the assumption that incidents of false flange contact are normally distributed about the critical value. For average lateral forces equal to FCRIT, there is therefore a 50/50 chance of false flange contact. As lateral forces decrease away from FCRIT, the probability of false flange contact rapidly decreases; as lateral forces rise above FCRIT, the probability rapidly increases. Figure 6.11 shows the standard normal density function where X represents the difference between the lateral force and the critical lateral force. Q(X), the probability of false flange contact, is the area under the curve to the right of X.

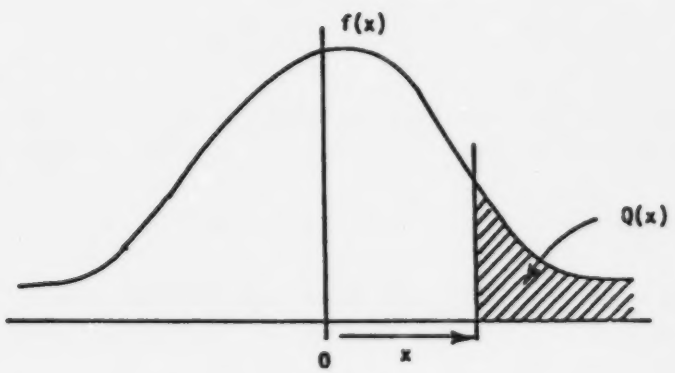


Figure 6.11 Density function for a standard normal variable

$$X = \frac{FCRIT - YMU}{STDEV}$$

where: FCRIT = critical lateral force for false flange contact

YMU = average lateral force as determined from the L/V ratio for the axle

STDEV = standard deviation of false flange contact incidents (assumed to equal standard deviation of lateral loads)

Q(X) = the probability estimate for false flange contact.

A numerical approximation of the normal cumulative distribution function is used[10] to calculate the possibility of false flange contact. For average lateral force less than FCRIT (X 0),

$$Q(X) = \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}} (a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5)$$

where: $t = \frac{1}{1 + rX}$

$r = 0.231642$

$a_1 = 0.31938$

$a_2 = -0.35656$

$a_3 = 1.78147$

$a_4 = -1.82126$

$a_5 = 1.33027$

For cases where the average lateral force is greater than FCRIT (X<0), then $Q(-X) = 1 - Q(X)$. This gives values of Q(X) between 0.50 and 1.0.

6.24 Subroutine WR

Subroutine WR calls the routines which perform the contact stress calculation, wear and batter rate estimation, and cycle loading calibra-

10 Abramowitz and Stegrin, Handbook of Mathematical Functions, U.S. National Bureau of Standards, New York, 1968, pp. 931-932.

tion for the fatigue life calculation. It applies the calibration factors for wear and batter, includes the effect of false flanging on the low rail, if appropriate, and stores this information by wheel/rail contact location and vehicle axle. A wear summary is printed if OUT(3)=0.

6.25 Subroutine CNSTRS

Subroutine CNSTRS calculates the maximum normal stress at the various contant locations between the rail and the wheels. The theory is based on the general case of contact between two elastic bodies as described by Hertz.

To calculate the contact pressure, an estimate must be made of the principal radii of the two surfaces. In the case of a rail and a wheel, it is difficult to establish these values because of the continual process of wear and plastic flow. In this subroutine, values have been assigned which are believed to be reasonable estimates for semi-worn conditions. These estimates are based upon sample profiles of semi-worn wheels and semi-worn rails from the CN system. In the analysis a term has been included which attempts to model the changing high-rail head conditions as the gauge face is worn.

The calculation of the maximum contact stress assumes that the contact patch is elliptical and that the stress has an elliptical distribution over the contact patch. If the semi-axes of the contact ellipse are represented by the terms 'a' and 'b', then it can be shown that the maximum pressure is equal to one-and-one-half times the average pressure.[11]

$$q_0 = \frac{3}{2} \frac{P}{\pi ab}$$

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11 J.O. Smith, C.K. Liu, "Stresses Due to Tangential and Normal Loads on an Elastic Solid with Application to some Contact Stress Problems," Journal of Applied Mechanics, June 1953.
S. Timoshenko and J.N. Goodier, "Pressure Between Two Bodies in Contact, More General Case," Theory of Elasticity, McGraw-Hill, New York, 1951.

where: P = contact load, and

$$a = \left[m \frac{3\pi}{4} \frac{(k_1 + k_2)\ P}{(A + B)} \right]^{\frac{1}{3}}$$

$$b = \left[n \frac{3\pi}{4} \frac{(k_1 + k_2)\ P}{(A + B)} \right]^{\frac{1}{3}}$$

The above expressions include several constants which are determined by the principal curvatures of the contacting bodies, and the physical properties of the two materials.

$$k_1 = (1 - \upsilon_1^2)/\pi E_1$$

$$k_2 = (1 - \upsilon_2^2)/\pi E_2$$

where: υ = Poisson's ratio (0.30 for steel)

E = Young's Modulus (30×10^6 psi)

$$A + B = \frac{1}{2} \left(\frac{1}{R_1} + \frac{1}{R_{11}} + \frac{1}{R_2} + \frac{1}{R_{22}} \right)$$

where: R_1 = radius of wheel

R_{11} = transverse radius of wheel

R_2 = longitudinal radius of rail (∞)

R_{22} = transverse radius of rail head.

The constants 'm' and 'n' are determined by the ratio of B-A to A+B. If

$$\cos \theta = \frac{B-A}{A+B}$$

where: $B-A = \frac{1}{2}\left[\left(\frac{1}{R_1} - \frac{1}{R_{11}}\right)^2 + \left(\frac{1}{R_2} - \frac{1}{R_{22}}\right)^2 + 2\left(\frac{1}{R_1} - \frac{1}{R_{11}}\right)\left(\frac{1}{R_2} - \frac{1}{R_{22}}\right)\cos 2\varphi\right]^{\frac{1}{2}}$

φ = angle of misalignment between the princpal curvatures,

then the values of 'm' and 'n' can be taken directly from Table 6.2.

TABLE 6.2

VALUES OF CONSTANTS 'N' AND 'M'

0 =	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
m =	2.731	2.397	2.136	1.926	1.754	1.611	1.486	1.378	1.284	1.202	1.128	1.061	1.000
n =	0.493	0.530	0.567	0.604	0.641	0.678	0.717	0.759	0.802	0.846	0.893	0.944	1.000

The contact stress as calculated in this subroutine can be broken down into the principal stresses:

$$\sigma_x = -2\upsilon q_0 - (1-2\upsilon)q_0 \frac{b}{a+b}$$

$$\sigma_y = -2\upsilon q_0 - (1-2\upsilon)q_0 \frac{a}{a+b}$$

$$\sigma_z = -q_0$$

In the calculation of wear and plastic flow, the value of σ_z is used. In the fatigue analysis a modified value of σ_x is used.

6.26 Subroutine WEARMD

Subroutine WEARMD is called upon to estimate the metal losses and deformations due to the passage of the wheels under rolling/sliding contact. Previously-called subroutines (CREEP and CNSTRS) supply the creep rates, contact stresses and friction factors which are then used in an empirical analysis to determine rates of adhesion/abrasive wear and cumulative plastic deformation.

Adhesive/Abrasive Wear

Laboratory results indicate that two modes of adhesive/abrasive wear exist. When the creep rates and contact stresses are sufficiently low, a 'mild wear' situation exists. This region is characterized by the deposition of a black powder which is composed of 80 per cent oxide and 20 per cent metallic iron. As the stress and creep increases beyond a transition zone, 'severe wear' predominates. This wear regime is characterized by deposition of a grey material that is 100 per cent metal. It is more flake-like in appearance. Figure 6.12 presents an estimate of the transition zone for standard rail steel under dry conditions.

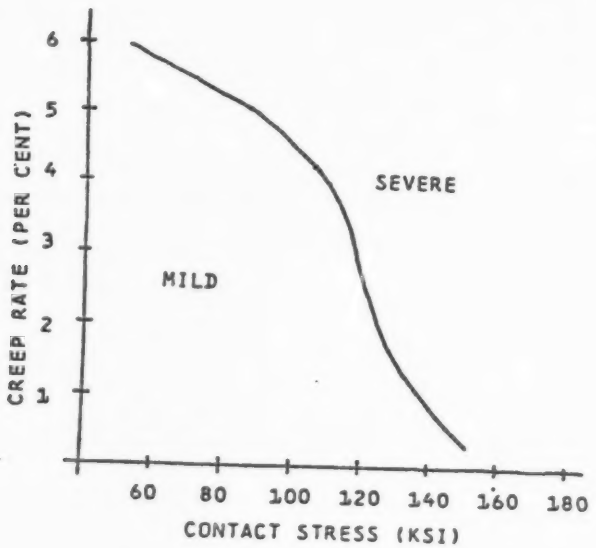

Figure 6.12 Transition zone for mild to severe wear

As lubrication and metallurgy change, so does the location of the transition zone. It is found that if the limiting friction factors are decreased by increased humidity or lubrication, or if the rail hardness is increased by changes in metallurgy, the transition zone is shifted away from the origin; that is, higher contact stresses and/or creep rates are required for severe wear to occur. The shift in the transition zone results in a reduction of the occurrence of severe wear. The wear rate surface for a given lubrication, metallurgy case is shown in Figure 6.13.

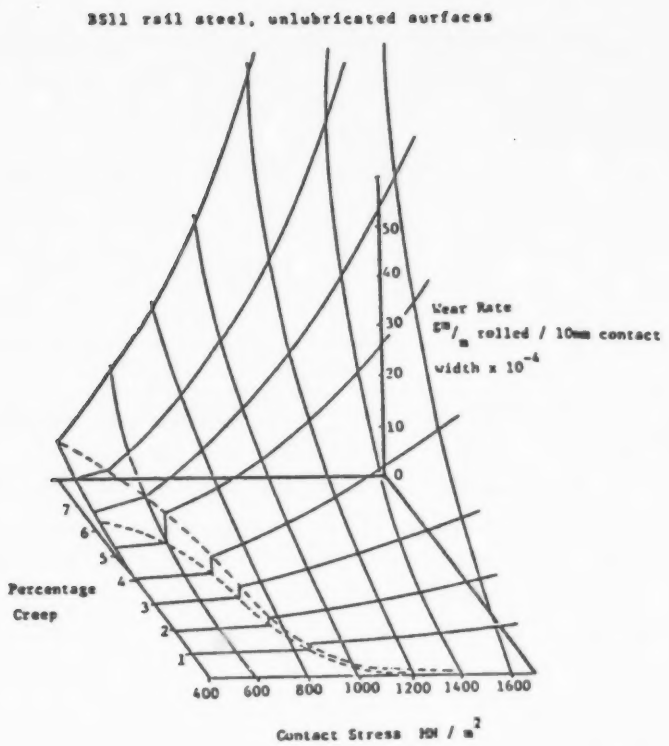

Figure 6.13 Wear rate vs contact stress and percentage creep12

An example of this type of transition shift can be seen on the gauge face in curves. Because of the very high slip rates, severe wear predominates. If the rail is lubricated or if the hardness of the rail is increased, the severe wear can be reduced or even eliminated, thereby greatly increasing the life of the rail.

Lubrication results in a marked decrease in the limiting friction factor. Table 6.3 shows ranges of limiting friction factors, 'f', for different rail surface treatments.

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12 T.M. Beagley, "Severe Wear of Rolling/Sliding Contact," Wear, Vol. 36, 1976, pp. 317-335.

TABLE 6.3

LUBRICATION EFFECT ON LIMITING FRICTION FACTOR

Treatment	f
dry steel	0.5 -0.6
wet	0.15-0.35
oil	0.05-0.15

Measured data available at the time when WEARMED was written indicated rates of wear for creep values of 5.3 and 2.0 per cent. For other creep rates, the wear rate is adjusted, assuming that it varies as the square of the creep rate. From the measured data a functional relationship was developed for adhesive/abrasive wear which took into consideration the creep rate and contact stress. The wear estimates are adjusted for different rail metallurgies and for lubrication conditions.

For the calculation of wear, the friction factors and creep rates are taken from subroutine CREEP and the contact stresses from subroutine CNSTRS. Metallurgical properties are based on the Brinell Hardness of the rail.

Cumulative Plastic Flow

Plastic flow of the rail head is due to high contact loads associated with tangential forces.13 When the contact stresses are above a limit known as the 'shakedown' of the material, cumulative plastic flow occurs. This shakedown limit is a function of the shear strength of the material and the conditions of friction and creep. Figure 6.14 shows the shakedown limits of standard rail steel for different friction factors.

13 J.E. Merwin, K.K. Johnson, "An Analysis of Plastic Deformation in Rolling Contact," Proc. Inst. Mech. Eng., Vol. 177, No. 25, 1963. G.M. Hamilton, "Plastic Flow in Rollers Loaded Above the Yield Point," Proc. Inst. Mech. Eng., Vol. 177, NO. 25, 1963.

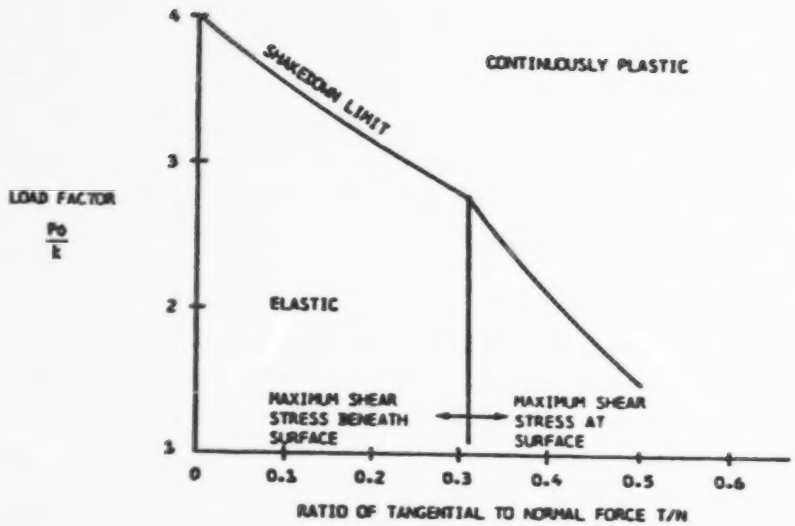


Figure 6.14 Shakedown limits for standard rail steel

If the conditions of stress in the rail exceed the shakedown limit, then cumulative plastic flow will occur. If the stresses are below the shakedown (even if some of the rail is stressed beyond its yield), then the material will reach a steady state where the internal residual stresses are sufficient to stop any further flow. The rate of plastic flow is a function of the amount the actual contact stresses exceed the shakedown limit.

6.27 Subroutine CYCRAT

Subroutine CYCRAT is the first of two subroutines used to predict the fatigue life of the rail. CYCRAT calculates the stress environment in the rail head due to the combined application of normal and tangential loads and then uses a standard S-N curve and modified Goodman diagram to calculate cycle ratios for various depths in the rail head.

In the stress analysis, both contact and bending stresses are considered. It is assumed that the rail is supported by a continuous elastic structure in the calculation of the bending stresses. Bending moments are evaluated, taking into consideration the effects of neighbouring axles. Bending stresses at various depths are found using the standard beam formula.

Contact stresses, including the normal and tangential loads, are predicted using Hertz theory of contact between elastic bodies. The program uses the value of the maximum contact pressure as calculated in subroutine CNSTRS. Tangential loads are added using the values of friction calculated in subroutine CREEP. The directions of the forces and the dimensions of the contact patch are considered in the analysis using the appropriate parameters from the two subroutines.

Working from the assumption that the contact pressures have an elliptical distribution, as shown in Figure 6.15, factors for determining the maximum and minimum stresses within the rail have been calculated. This has been performed in subroutine CONCEN for a set of depths within the rail head for a unit-normal load acting on a contact patch with a major axis of unit length. A table look-up for the appropriate maximum and minimum stress factor is performed by searching for the actual friction factor at the contact and for the level in the table which corresponds to the level in the rail head. These are then used to calculate the maximum and minimum stresses at the level. The magnitudes of the factors are scaled according to the actual normal load, and the depth to which they are to be applied are scaled inversely as the dimension of the major axis of the contact patch.

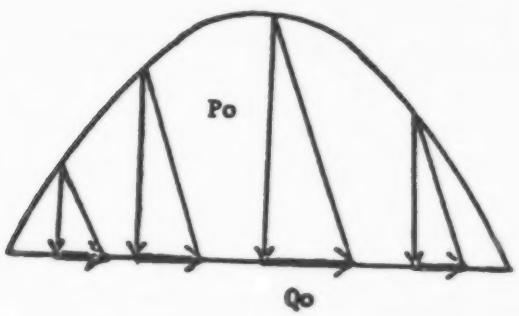


Figure 6.15 Elliptical distribution of normal and tangential loads

From these a mean stress and an amplitude are determined. A modified Goodman diagram, as shown in Figure 6.16, is used to find the required endurance limit for the rail under the given load conditions. The endurance limit (S_e) is used to calculate the number of cycles to failure. Figure 6.17 represents the S-N curve for standard rail steel.

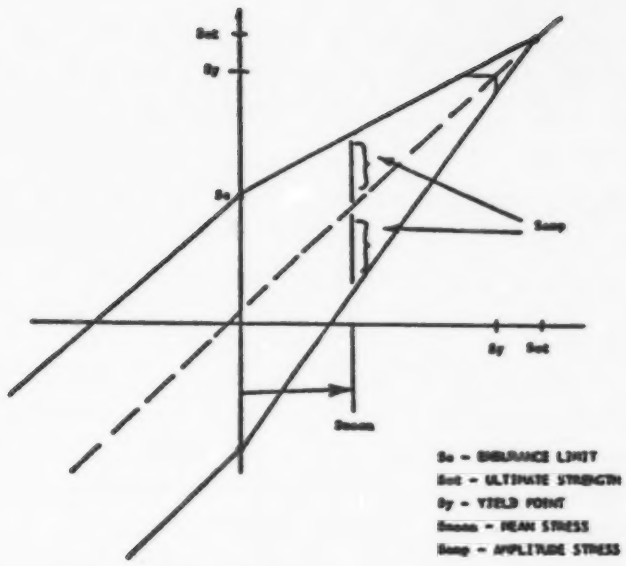


Figure 6.16 Modified Goodman diagram showing the mean and amplitude stresses which specify the required endurance limit, S_e

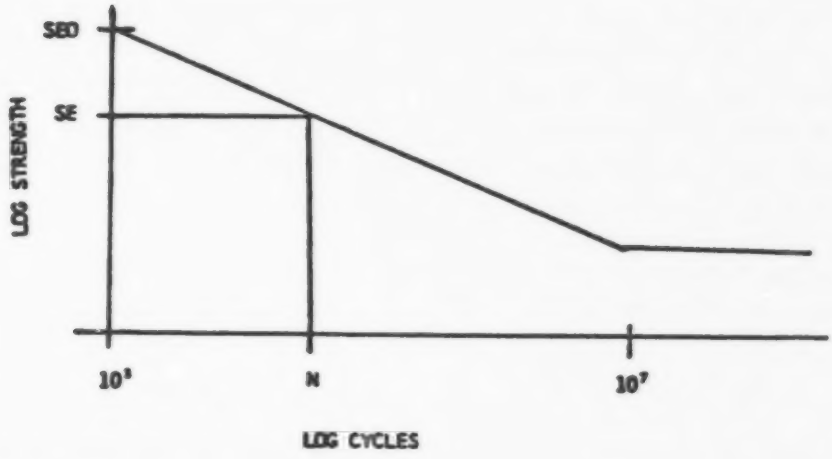


Figure 6.17 S-N curve for standard rail steel showing the appropriate life (N) for the precalculated endurance limit, S_e

With the number of cycles to failure calculated (N), the cycle ratio is evaluated using the actual number of cycles the rail is stressed.

Let: n = actual cycles, and

N = cycles to failure,

then the cycle ratio for a given load condition is

$$\text{cycle ratio} = \frac{n}{N}$$

For many different load conditions, the fatigue life of the rail is taken to be when the sum of the cycle ratios reaches a value between 0.7 and 2.2; that is

$$\sum \frac{n}{N} = 0.70 \text{ to } 2.2$$

This is the Palmgren-Miner cycle ratio summation theory and is widely used in design to account for fatigue.

Cycle ratios are calculated for each of the depth intervals, for each different vehicle type. The overall fatigue damage to the rail at each depth is taken to be the sum of the individual cycle ratios. The next step is to calculate the total million gross tons of traffic before the fatigue life is reached. This calculation must include the effects of wear and plastic flow and is therefore dependent on the entire wear model for accuracy.

Subroutine FATLIF is used to combine the effects of wear and stress to estimate the fatigue life.

6.28 Subroutine LIFE

Subroutine LIFE estimates the life of the rail, given the wear rates of the high-rail head, low-rail head and high-rail gauge face. The life calculation is the one developed and used by Canadian National. Its form is:

$$\text{LIFE} = 2 \times \left[\frac{\text{TRANSPOSAL WEAR ALLOWANCE}}{\left(\frac{\text{HIGH RAIL}}{\text{WEAR RATE}}\right) + \left(\frac{\text{LOW RAIL}}{\text{WEAR RATE}}\right) + \left(\frac{\text{GAUGE FACE}}{\text{WEAR RATE}}\right)} \right]$$

This formulation can be replaced by a more appropriate one, if known, when making estimates for other railways.

6.29 Subroutine PASS2

Subroutine PASS2 calls the routines required to perform the cost calculations. It uses the wear rates and batter rates at each contact location attributable to each car class to revise the total traffic wear and batter rates. The new wear and batter rates with the deletion of an entire traffic class are used in the incremental cost calculation. The new wear and batter rates with the specified marginal tonnage of the car class removed (see Section 4 on the Calibration file) are used in the marginal cost calculation. The fatigue life calculation is highly non-linear. Subroutine PASS2 therefore adjusts the stress cycles according to the change in traffic tonnage and recalls the fatigue life estimation routine for both the incremental and marginal cases. PASS2 prints the cost summary if OUTP(7)=1.

6.30 Subroutine FT

Subroutine FT, for the high rail and low rail, passes the appropriate table of stress cycles, the total annual tonnage traffic and wear rate to subroutine FATLIF where the fatigue life is estimated. FT also calls LIFE first to estimate the wear life of the rail and then to estimate the batter life of the routine. The subroutine determines the high-rail life and the low-rail life. The rail life is the minimum of the wear, batter and fatigue life.

6.31 Subroutine FATLIF

Subroutine FATLIF brings together the wear rates from subroutine WEARMD and cycle ratios determined in subroutine CYCRAT to predict a time to failure based on the Palmgren-Miner cumulative damage cycle ratio summation theory.

The life calculation procedure is iterative and combines the effect of wear and fatigue. As the rail is worn away, there is a change in the stress environment affecting each of the remaining depth levels. The new stress environment for a level is the same as that experienced by the level immediately above it at the time before the uppermost slice was removed by wear. This is the basis for incrementing the cycle ratios.

The location where the cycle ratios are observed is chosen to be slightly below the surface of the rail. This is required to account for the non-elastic behaviour of the uppermost slices in the rail head.

The uppermost slice of the rail head is assumed to be removed by wear and plastic flow. The cycle ratios for each level in the rail are incremented to reflect the new stress environment. At a fixed depth below the existing surface of the rail, the sum of the cycle ratios is tested to determine whether it exceeds the critical value. If it has not, then the next uppermost slice of the rail head is removed and a new cycle ratio sum is calculated. If it has exceeded the critical value, then the fraction of a slice which must be removed to reach the critical value is determined. This fraction plus the total number of slices removed is used to estimate the time to failure.

The critical value for the cycle ratios, normally considered to be between 0.70 and 2.2, is set in the calibration file. The fixed depth at which the test is made is also in the calibration file.

6.32 Subroutine COSTS

Replacement Value Costing Procedure

The costing section of the CIGGT Rail Wear Cost Model employs a replacement value methodology to estimate incremental and marginal costs of rail wear. The approach involves two separate computations. For the first, the traffic over the rails which would be replaced by a heavier or better section is costed on the basis of both the life and costs that would apply were like-for-like replacement reasonable. The second presumes a replacement policy and computes the respective changes for both the cost and life that would apply to the replacement rails. The appropriate charge is the maximum of the two.

Rail wear is computed for specific, homogeneous line segments, and translated through wear limits to expected rail life for specific traffic/track combinations. The impact of different traffic classes is quantified as the increase in rail life determined by the detection of specific traffic classes or by the deletion of portions of specific traffic classes. The problem, then, reduces to a conversion of these rail lives to costs. The life data as generated are not compatible with 'conventional' statistical costing techniques insofar as they exist. The method chosen bases traffic-specific charges on the differences in expenditure patterns that arise from different rail renewal cycles. Thus, the total cost for all traffic on the line is given by the yet unspecified function,

$$C_{\Sigma} = f\,(L_s^{\Sigma}, k, M, t, \ldots)$$

where: L_s^{Σ} is the expected rail life for track section 's', given the total traffic

k is the cost of capital

M is the unit price of a rail changeout

T is the tax rate.

The total charge for a particular traffic class, 'i', is calculated on a decremental basis as:

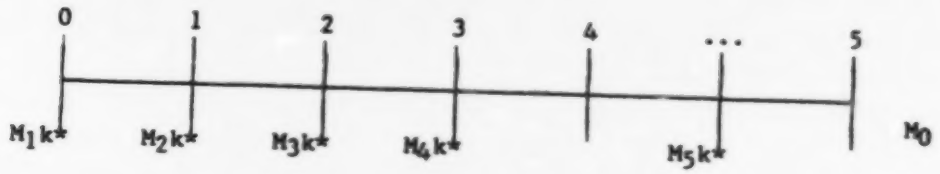
$$C_i = [f(L_s^{\Sigma}, k, M, T, \ldots) - f(L_s^{\Sigma-i}, k, M, T, \ldots)]$$

where $L_s^{\Sigma-i}$ is the expected rail life if traffic 'i' were deleted.

Just as incremental costing is used to evaluate changes in expenditures due to the acceptance of new increments of traffic, charges for each class of traffic can be identified as the cost savings benefits from not carrying that class. When one considers the complexity that the use of historical prices for rail would pose -- even were they always known -- the only practical method of converting the changes in expenditures to charges involves some form of a replacement value technique.

A replacement value charge is determined by multiplying the installed replacement price of the rails by a charge rate, 'k*', applicable to rails. This charge must accommodate the expected future replacement prices and, when discounted, yield a nominal return equal to the cost of capital.

For an initial purchase price of 'a_0', projected replacement prices in year 't' of 'a_t', an economic life of 'n' years and a cost of capital 'k' per cent, the charge cash flows would be



Discounting,

$$a_0 = k^* \sum_{t=1}^{n} M_t \, (1+k)^{-t}$$

and solving for the charge rate, 'k*',

$$k^* = \frac{M_0 \, (1+k)^n}{M_t \, (1+k)^{n-t}}$$

This is of the form of a capital recovery factor, and could be treated as a capital recovery factor were rail replacement prices to remain constant.

Dealing for convenience with projected rail prices which change at a constant escalation factor (which can be either positive or negative), the replacement-value-costing charge rate is given by

$$k^* = \left[\frac{k-\Delta}{1+\Delta}\right] \left[\frac{(1+k)^n}{(1+k)^n - (1+\Delta)^n}\right]$$

This also looks like a capital recovery factor formulation, but for a rate

$$k' = \left[\frac{1+k}{1+\Delta} - 1\right]$$

which is analogous to a real rate of return, but only for the corporate entity, not the investors, and only for the specific asset,[14] not for the whole railway system. The replacement value charge, however, is not based on the use of an overall real (or inflation-adjusted) return.

In the COSTS subroutine, the variables used are:

ROK = k = rate of return on invested capital

DELTC = Δ = cost escalating rate applicable to rails (in place)

KPRIME = k' = charge rate.

The charge rate is calculated according to the equation:

$$\text{KPRIME} = \left[\frac{1+\text{ROK}}{1+\text{DELTC}} + 1\right] = \frac{\text{ROK} - \text{DELTC}}{1 + \text{DELTC}}$$

Given the predicted rail life, the replacement value costing annual charge rate for the total traffic, 'KS', can be estimated from:

$$\text{KS} = \left[\frac{\text{ROK-DELTC}}{1+\text{DELTC}}\right] \left[\frac{(1-\text{ROK})\text{SL}^{(\text{LL})}}{(1+\text{ROK})^{\text{SL(LL)}} - (1+\text{DELTC})^{\text{SL(LL)}}}\right]$$

$$\text{KS} = \frac{\text{KPRIME}\ (1+\text{KPRIME})^{\text{SL(LL)}}}{[(1+\text{KPRIME})^{\text{SL(LL)}} - 1]}$$

where SL(LL) is the expected life of the rail in years under current traffic.

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14 The escalation rate applicable to a class of assets may differ markedly from the inflation rate upon which real rate-of-return theory is based. Even under current inflationary conditions, a negative rate would apply to computers.

A useful innovation, advanced in concept by T. Guins of the AAR, has been developed and included in the evaluation routine. Fundamentally, the CIGGT model assumes new rail at the start of a cycle. This assumption is implicit in the equivalent annual cost methodology, based on rail replacement cycles, and is generally appropriate for costing purposes. Guins suggested, however, that for system conversion of freight car tracks where existing rail showed a wide age distribution, this might not be accurate. Investigation indicated that the CIGGT assumption understated the benefits for conversion.

To examine the importance of this inaccuracy, an additional option, which assumes partly-worn rail at the beginning of the cycle, was incorporated into the Rail Wear Cost Model and the sensitivity to this effect studied. While for most cases the impact is slight to negligible, under certain circumstances (where lives are long and the changes in life are dramatic), it is indeed significant.

With the existing traffic pattern, maintenance takes place in ℓ_1 year cycles forever. The change in wear pattern due to the improvement in dynamic load capabilities allows this maintenance cycle to take place every ℓ_2 years forever. This is illustrated in Figure 6.18.

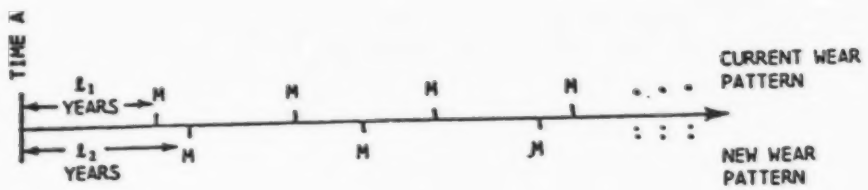

Figure 6.18 Time line showing maintenance cycles before and after. M represents cost of one cycle (assuming new track).

At a cost of capital of 'k', and taking time 0=A (i.e. at the end of a maintenance cycle), the present value of the expenditures on the maintenance cycle required by the current wear pattern is:

$$\sum_{t=1}^{\infty} M(1+k)^{-\ell_1 t}$$

Similarly, the present value of the maintenance cycle, given the new wear pattern, is:

$$\sum_{t=1}^{\infty} M(1+k)^{-\ell_2 t}$$

The present value of the cost savings (assuming $\ell_2 > \ell_1$) due to the change which gives rise to the new wear pattern is

$$M\left[\sum_{t=1}^{\infty} (1+k)^{-\ell_1 t} - \sum_{t=1}^{\infty} (1+k)^{-\ell_2 t}\right]$$

The assumption that the change in wear patterns occurs exactly at the end of a maintenance cycle is too rigid. The cost flows resulting from starting 'p' proportion into the maintenance cycle are shown in Figure 6.19.

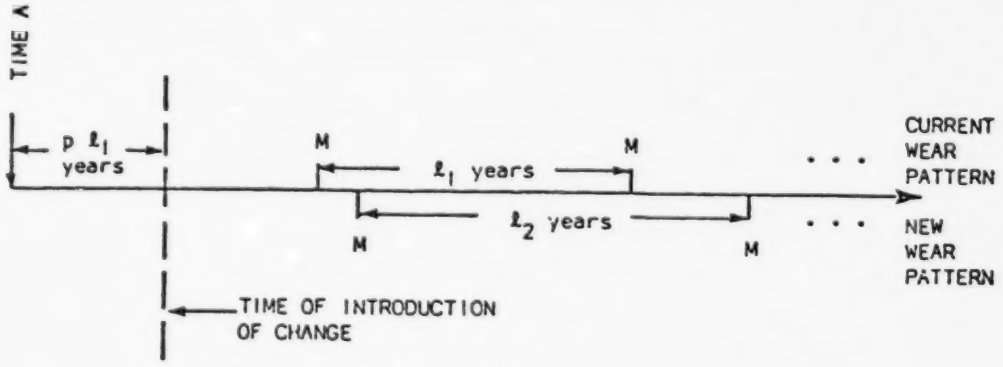

Figure 6.19 Maintenance cycle time line for partly worn track

Because the change in wear patterns only affects the life remaining in the maintenance cycle, the new (ℓ_2 year) cycle must start earlier by $p(\ell_2-\ell_1)$ years. Thus the present value of the new maintenance cycle is

$$(1+k)^{p(\ell_2-\ell_1)} \sum_{t=1}^{\infty} M\,(1+k)^{-\ell_2 t}$$

To correct the present values for the change in time t=0 from A to the introduction of the change, both present value streams must be compounded for p x ℓ_1 years. Thus the present value of the difference is

$$PV = M\left[(1+k)^{\ell_1 p}\right]\left[\sum_{t=1}^{\infty}(1+k)^{-\ell_1 t} - (1+k)^{p(\ell_2-\ell_1)}\sum_{t=1}^{\infty}(1+k)^{-\ell_2 t}\right]$$

$$= M\left[(1+k)^{\ell_1 p}\right]\left[\frac{1}{(1+k)^{\ell_1}-1} - \frac{(1+k)^{p(\ell_2-\ell_1)}}{(1+k)^{\ell_2}-1}\right]$$

$$= M\left[\frac{(1+k)^{\ell_1 p}}{(1+k)^{\ell_1}-1} - \frac{(1+k)^{\ell_2 p}}{(1+k)^{\ell_2}-1}\right]$$

For an even distribution of track wear, the present value for the mean level of p is represented by the integral of PV evaluated over the interval p = [0,1].

The integral formulated is solved as follows:

$$\int_{p=0}^{p=1}\left[\frac{(1+k)^{\ell_1 p}}{(1+k)^{\ell_1}-1} - \frac{(1+k)^{\ell_2 p}}{(1+k)^{\ell_2}-1}\right] dp$$

where $k > 0$ and k, ℓ_1, ℓ_2 are not functions of p,

$$= \frac{1}{(1+k)^{\ell_1}-1}\left[\frac{(1+k)^{\ell_1 p}}{\ell_1 \ln(1+k)}\Bigg|_{p=0}^{p=1}\right] - \frac{1}{(1+k)^{\ell_2}-1}\left[\frac{(1+k)^{\ell_2 p}}{\ell_2 \ln(1+k)}\Bigg|_{p=0}^{p=1}\right] + C$$

$$= \frac{1}{(1+k)^{\ell_1}-1}\left[\frac{(1+k)^{\ell_1}-1}{1\ln(1+k)}\right] - \frac{1}{(1+k)^{\ell_2}-1}\left[\frac{(1+k)^{\ell_2}-1}{2\ln(1+k)}\right] + c$$

$$= \frac{\ell_2-\ell_1}{\ell_1\ell_2\ln(1+k)} + C \qquad \text{[C here is zero]}$$

This represents the appropriate present value cost savings in perpetuity change rate.

In subroutine COSTS, incremental and marginal costs are calculated using the method which assumes new rail at the beginning of the cycle and for the case which assumes partly-worn rail at the begining of the cycle. The effects of deletion of each car weight class from the total annual traffic load on rail lives and the incremental and marginal costs associated with each car weight class are printed at the end of a run.

6.33 Subroutine PRNT

Subroutine PRNT outputs to the printer file the engineering summaries. The level of detail is determined by the output parameter OUTP(6). If OUTP(6) = 0, no summary is printed. If OUTP(6) = 1, then a detail summary of wear rates, batter rates and fatigue lives by location and overall wear lives and batter lives is printed. If OUTP(6) = 2, then only a summary of wear rates and batter rates in inches per 100 MMGT and in inches per year is given. If OUTP(6) = 4, only a summary of wear lives, batter lives and fatigue lives is given. If OUTP(6) = 5, wear rates and wear lives are printed.

7. CALIBRATION

Calibration of the Rail Wear Cost Model to data which describe the particular traffic, track and maintenance conditions and the associated wear rates found on specific railways is an integral part of the model development process. The individual mechanisms which contribute to, or which interact with other mechanisms to contribute to, rail degradation are represented in the model by both theoretically-based and empirically-based sets of equations. These provide a reasonable estimate of the behavior of the vehicle/track system (under the chosen simplifying assumptions) as characterized by the small-scale wheel/rail interactions and the cumulative effects of these interactions, but not in absolute terms. Calibration provides this (scaling) link. It bridges the gap between what is known -- the parameters which can be measured and the relationships which can be modelled -- and what is not known -- the parameters which are difficult to measure and the relationships which are not well understood or are too complex to model in detail.

The Rail Wear Cost Model has been calibrated to wear and life data from the Quebec North Shore and Labrador Railway (QNS&L). The QNS&L is a single-track iron-ore railway handling approximately 54 million gross tons annually, with about 80 per cent of axle loads exceeding 31 tons and 40 per cent of the total mileage on curved track. The model has also been calibrated to data from the Quebec Cartier Railway, another high-density, high-curvature, single-track, iron-ore railway, and to data from the BC South Line, a high-curvature CN main line.

A comparison of the average wear on the high-rail head, low-rail head and high-rail gauge face for standard carbon rail and for heat-treated rail found on QNS&L curved trackage with values produced by the Rail Wear Cost Model is illustrated in Figures 7.1, 7.2 and 7.3. Note that the model estimates for wear on heat-treated rail are consistently lower than the QNS&L measurements. This adjustment has been made to obtain better agreement with calibration data for heat-treated rail on other railways. Even as low as the shifted rail-wear estimates are, the lives predicted by the Rail Wear Cost Model are still on the low end of the range of rail lives found for heat-

treated rail on other railways. It would appear that either the metallurgy for QNS&L heat-treated rail is different in some way from that found for the other railways for which calibration was done, or that the Brinell Hardness of the QNS&L heat-treated rail was lower, on average, than the hardness reported. The latter situation is more likely.

It is important to note that the model has only been calibrated to data from high-density, high-quality track. It is at this upper end of the scale that traffic, track, maintenance and wear data of sufficiently high quality and detail have been available. Therefore, at this stage, estimation of rail wear and associated costs on low-density, poor-quality track should be considered to be beyond the reliable range of the model. As data become available, it will be possible to extend the range of applicability for the rail wear model.

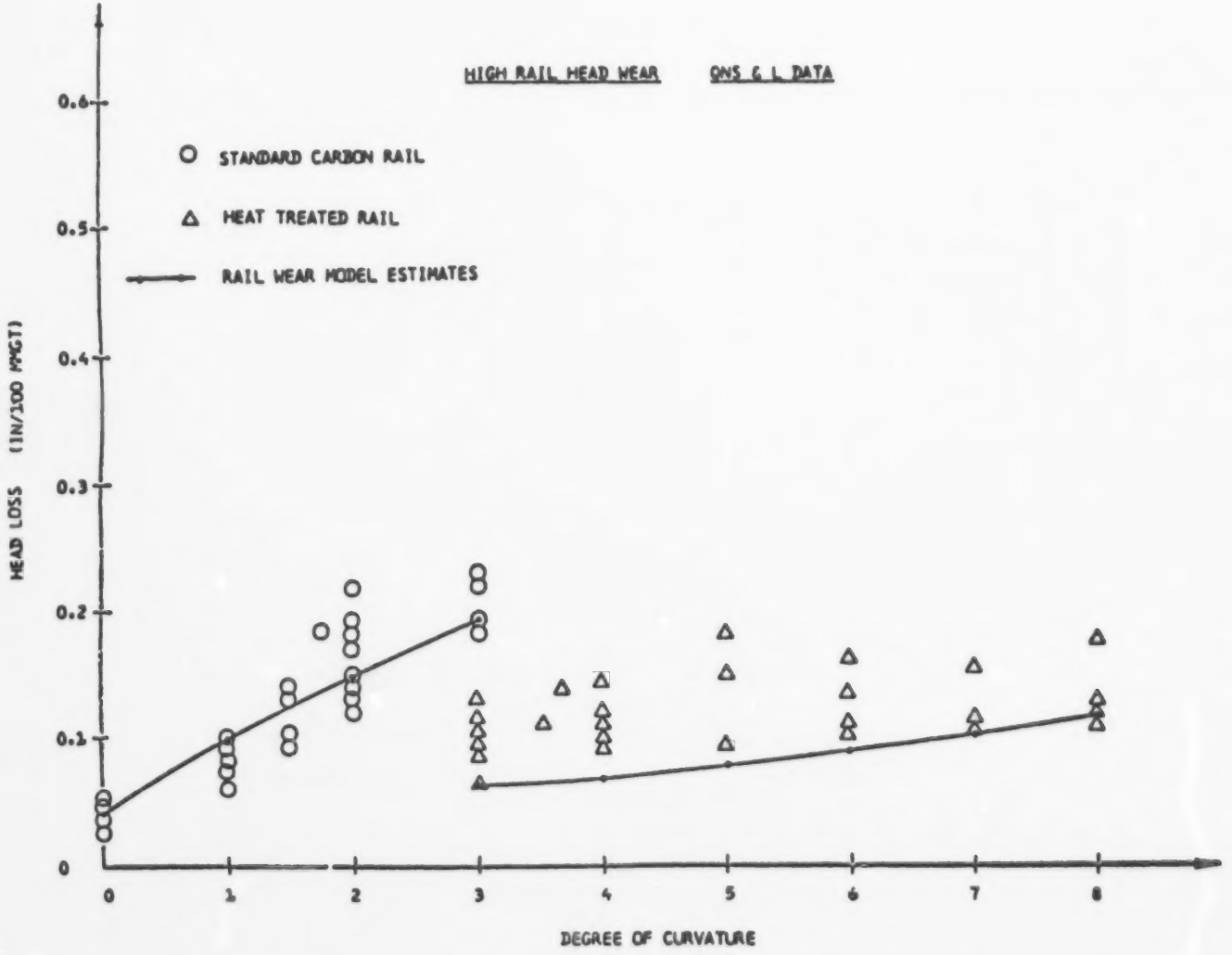

Figure 7.1 Calibrated high-rail head wear

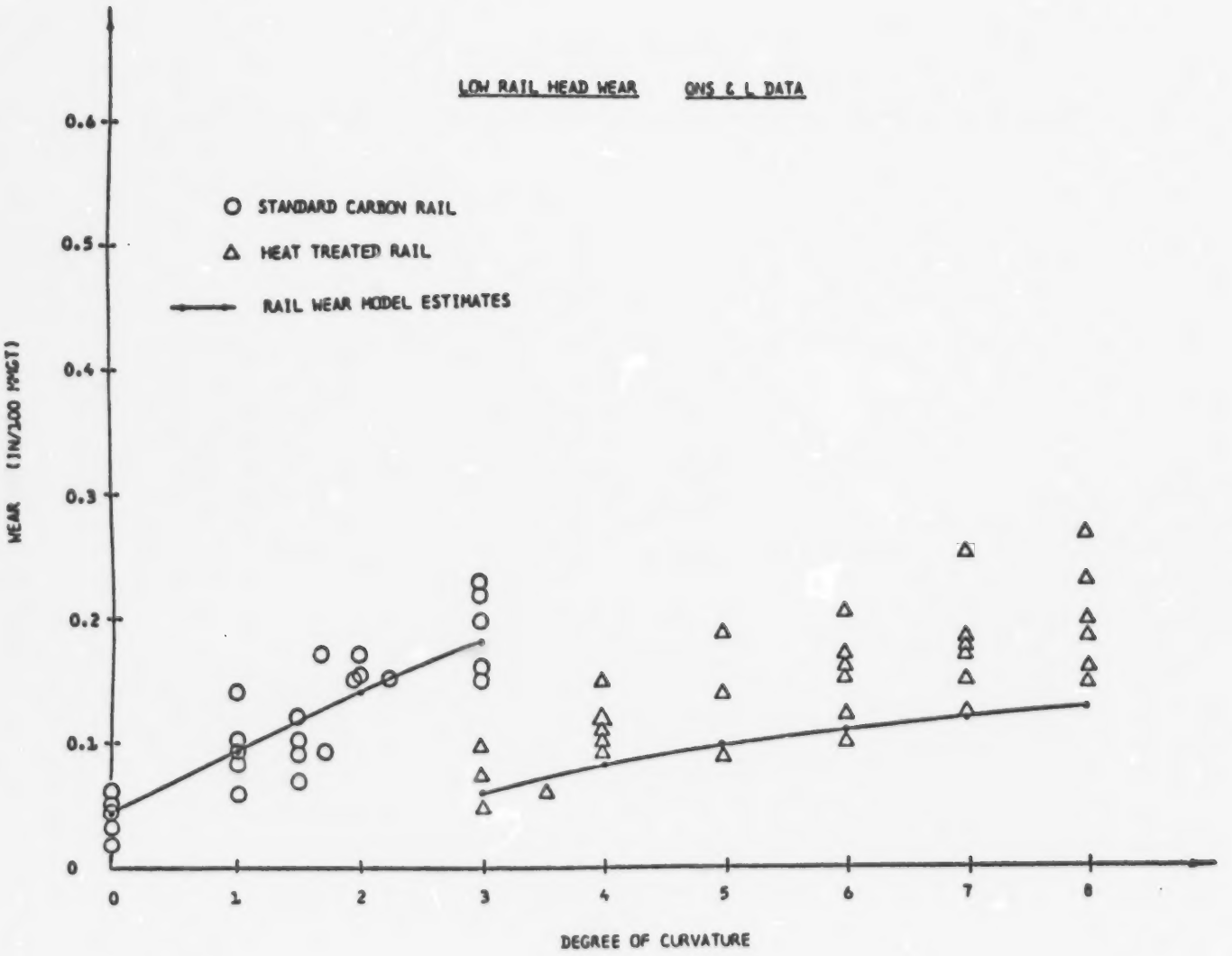

Figure 7.2 Calibrated low-rail head wear

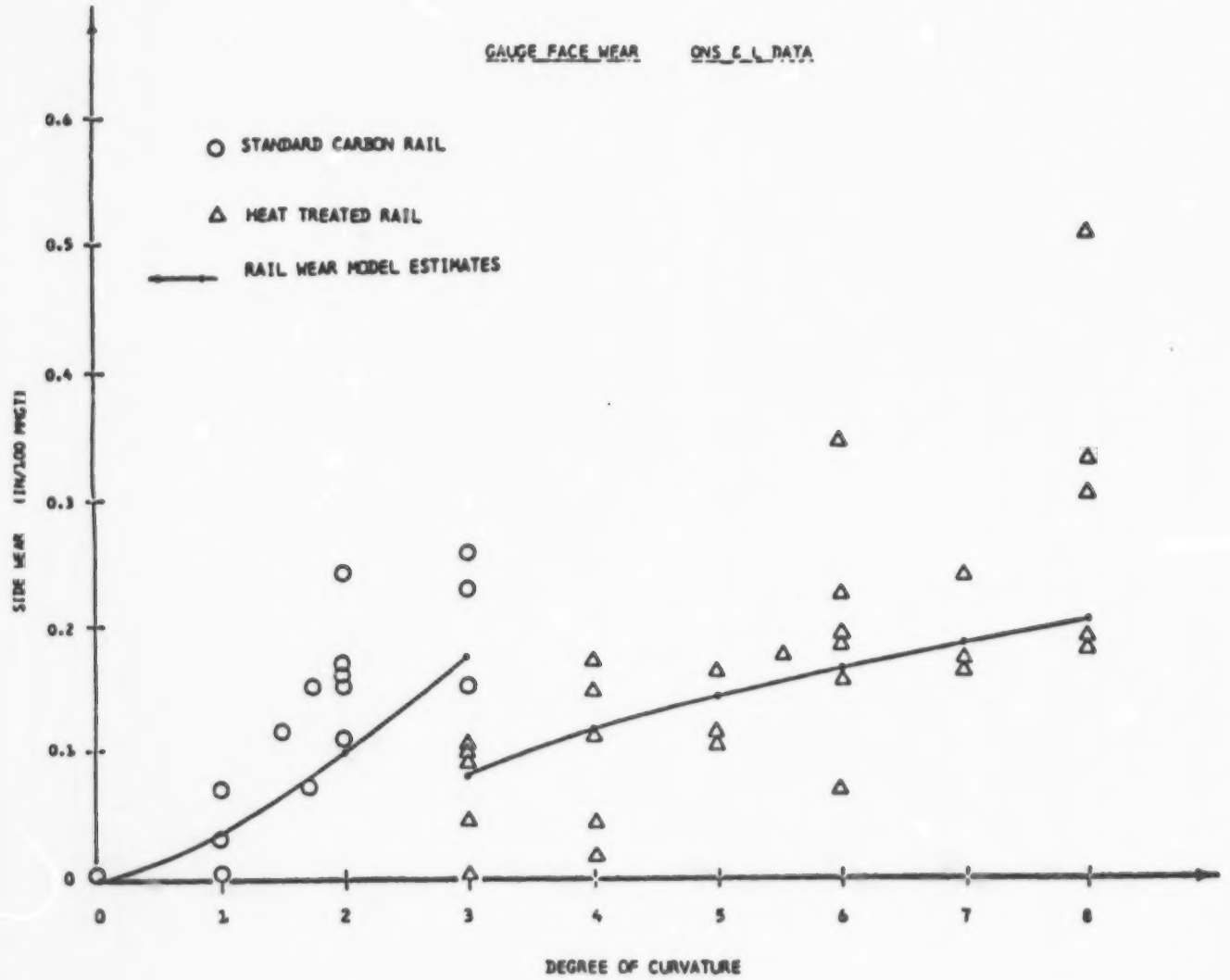

Figure 7.3 Calibrated gauge-face wear

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APPENDIX A

RAIL WEAR COST MODEL PARAMETER LIST

A	-radial distance down to flange contact, dimension of contact patch along direction of sliding on rail head in CONCEN (assumed A = 1, then scaled)
ADELTA	-change in A for CN profile
AIR	-scaling factor for air brake calculation, equal to empty car weight
ALPHA	-ASCII card image in FREEIN
AMX	-A - X in CONCEN
AOFA	-angle of attack in minutes
APX	-A + X in CONCEN
ARBHN	-storage array of Brinell hardness by location in FF
ARM	-moment arm for flange longitudinal force
ARTMW	-array storage of TMW's by axle and location
ASAV	-saved value of A
ASQ	-A squared in CONCEN
ASQ2	-2 times A squared in CONCEN
ASQ4	-4 times A squared in CONCEN
AVAB	-average of XA and XB semi-axis of contact patch
AXLE	-axles per truck of vehicle
AXLNAM	-character string '2AX 3AX'
AXLSAV	-save value of AXLE
B	-horizontal distance to flange contact (inches)
BAT1	-calculated total high rail batter in inches / 100 MGT
BAT2	-calculated total low rail batter in inches / 100 MGT
BATCR1	-high rail batter for a specific vehicle (in/car)
BATCR2	-low rail batter for a specific vehicle (in/car)
BATIN1	-high rail batter for a specific car (in/yr)
BATIN2	-low rail batter for a specific car (in/yr)
BATP1	-scale factor for P1 batter
BATP2	-scale factor for P2 batter
BATTR	-array storage of batter sums by rail (inches/MGT)
BETA1	-high rail slip vector angle
BETA1S	-array storage of high rail slip vector by position
BETA2	-low rail slip vector angle
BETA2S	-array storage of low rail slip vector by position
BETALL	-array storage of slip vectors by rail position
BHN	-Brinell hardness number
BHNCOM	-array containing BHN
BHNSAV	-save value of BHN
BHNX	-BHNX(1) high Brinell hardness, BHN(2) low Brinell hardness
BLANK	-blank character string
BLANKS	-blank character string
BLIFE	-batter life in years
BLIFEC	-batter life in cars
BLIFEM	-final batter life in MMGT
BM1	-intermediate value in calculation of maximum bending moment, function of E, RI and U
BM2	-intermediate value in calculation of minimum bending moment, function of E, RI and U
BMMAX	-maximum bending moment
BMMIN	-minimum bending moment

```
BSMAX   -maximum bending stress
BSMIN   -minimum bending stress
BUFF    -buff load (lbf)
BUFFS   -array storage of buff loads by direction
C       -Hertzian contact deflection constant
C1      -constant used in CONCEN for setting position along rail
C2      -constant used in CONCEN for setting position along rail
C3      -constant used in CONCEN for scaling (equal to -CS/3.14159)
C4      -constant used in calculation of cycles to failure
C5      -2 times the number of cars per cycle per class per year
CALABR  -calibration factor for abrasion, (CALABR(1) on high rail head,
CALABR   CALABR(2) on low rail head, CALABR(3) on high rail flange)
CALCYC  -factor to scale cycles by
CALFAT  -fatigue calibration
CALFIL  -calibration file number
CALOCO  -horsepower scale factor
CALPLF  -calibration factor for plastic flow (CALPLF(1) on high rail
CALPLF   head, CALPLF(2) on low rail head, CALPLF(3) on high rail flange)
CALPLS  -scale factor for batter in WR
CAR1    -abrasive wear on high rail head per car
CAR2    -abrasive wear on low  rail head per car
CAR3    -abrasive wear on high rail gauge face per car
CARS    -number of cars per class per year
CD      -track damping coefficient
CDT     -lumped equivalent track damping
CFANG   -cosine of flange angle
CFX1    -force in X direction for high rail, CRPFX by axle and position
CFX2    -force in X direction for low  rail, CRPFX by axle and position
CFXF    -force in X direction for   gauge  , CRPFX by axle and position
CFY1    -force in Y direction for high rail, CRPFY by axle and position
CFY2    -force in Y direction for low  rail, CRPFY by axle and position
CFYF    -force in Y direction for   gauge  , CRPFY by axle and position
CFZ1    -force in Z direction for high rail, CRPFZ by axle and position
CFZ2    -force in Z direction for low  rail, CRPFZ by axle and position
CFZF    -force in Z direction for   gauge  , CRPFZ by axle and position
CHARG1  -charge rate for high rail
CHARG2  -charge rate for low  rail
CHARGE  -average incremental charge assuming total rail replacement
         (cents/1000 ton-miles)
CHARGM  -average  marginal   charge assuming total rail replacement
         (cents/1000 ton-miles)
CHECK   -character string of numbers for use in FREEIN
CN      -number of cars
CNTSTS  -maximum stress on contact patch (S.I. units)
COMP    -factor to provide grade compensation of curves
CONE    -conicity of wheel
CONST1  -constant used in calculation of effective track mass in VDYN
CONST2  -constant used for making estimate of P1 and P2 forces in VDYN
COSB    -array storage of COSINE(BETALL) by rail position
COSTH   -cosine of vertical angle due to superelevation
CR      -rail radii of curvature assumptions (CR(1) high rail head,
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          CR(2) low  rail head, CR(3) high rail flange)
CRATIO    -cycle ratios based on actual applied stress cycles
CRPFX     -creep force in x direction
CRPFY     -creep force in y direction
CRPFZ     -creep force in z direction
CS        -factor for scaling stresses
CUM       -stress cycles to date
CW        -wheel radii of curvature assumptions (CR(1) high rail wheel,
           CR(2) low rail wheel, CR(3) high rail flange wheel)
CW2FF     -wheel raduis of curvature assumed for false flansing
CWR       -character string 'CWR', used in output
CYCLES    -number of stress cycles to failure based on S-N curve for the
           rail
D         -track curvature
DAVIS     -intermediate value for calculating rolling resistance using
           Davis equation
DB        -total available dynamic braking force (lbf)
DBDEL     -dynamic braking effect on L/V ratio
DBRF      -dynamic braking force per loco
DBS       -scale factor for normal operation and dynamic braking in resis-
           tance calculations
DBUFF     -scale factor for buff load effect on car (DBUFF(1) on locomot-
           ives, DBUFF(2) on cars)
DCT       -effect of gauge face wear on salvage value of rail
DCURV     -degree of curvature (degrees)
DEL       -angle of attack of wheel on curve
DEL1      -angle of attack on leading  axle
DEL2      -angle of attack on trailing axle
DELCUR    -curvature to reflect prehunting motion
DELL      -gauge widening factor
DELSAV    -saved value of DEL
DELSLI    -gauge of track divivded by raduis of curvature
DELT      -proportion of level above an even level fatigue has taken place
DELTC     -rail price escalator, default = 6%
DENOM     -intermediate value in calculation of stress in CONCEN
DESIGN    -design condition for consist in TRAIN
DIHF      -standard deviation of high frequency contact load
DILF      -low frequency dynamic load factor
DIP       -dip joint angle (radians)
DIPX      -loaded dip angle
DIRNAM    -character string 'FORWARD    BACKHAUL'
DIS1      -array storage of CHARGE by car
DIS2      -array storage of TOICST by car
DISK      -variable used inorder to rewind disk in PRNT, equal to 3
DISKHI    -factor to restore cycle count FSUMHI to disk form and remove
           incremental traffic cycles
DISKLO    -factor to restore cycle count FSUMLO to disk form and remove
           incremental traffic cycles
DOING     -dynamic braking force acting at car wheels, flag indicating
           decoding mode in FREEIN
DR        -character string in PASS2
```

DYNBRK -dynamic braking force acting at car wheels
E -Young's modulus of elasticity (for steel: 30,000,000 psi)
EI4 -4 x EI x RI
EI4M -EI4 (S.I. units)
EMPO -empty car axle loading
F1TOT -total vertical load on high rail
F2TOT -total vertical load on low rail
FACT -force per axle (lbs)
FANGLE -flange contact angle
FC -array storage of friction coefficients in CONCEN table, in subroutine VERT, the force due to car going around horizontal curve (kg-m/sec-sec)
FCRIT -critical lateral force for false flange contact
FCRITS -calibration factor fo FCRIT
FDELTA -change in flange angle for CN profile
FHF -flange horizontal force
FL -force on locomotive per axle, used in TRAIN
FLAG -flag indicating type of wear (none,mild or severe)
FLAGFF -array storage of FLAG values by axle in WR
FLAGS -array storage of FLAG values
FLIFE -fatigue life in MMGT
FLIFHI -final high rail fatigue life in MMGT
FLIFLO -final low rail fatigue life in MMGT
FLNF -normal force on flange
FNF -flange normal force
FRC -array storage of friction coefficients in stress concentration table, equal to FC in CONCEN
FRICTX -friction used in CONCEN
FSAVHI -saved FSUMHI by level in PASS2
FSAVLO -saved FSUMLO by level in PASS2
FSUM -cycle counts in FATLIF (equals FSUMHI or FSUMLO)
FSUMHI -cycle counts for high rail by level
FSUMLO -cycle counts for low rail by level
FSUMS -array storage of cycle ratios
FVF -flange vertical force including normal force
G -bulk modulus of rail
GAM -angle between coordinate systems for front and rear axles of truck (radians)
GF -gauge face wear (inches/MGT)
GG -shear modulus of rail
GRAD -grade
GRD -grade (S.I. units), local value of GRAD in TRAIN
GRDSAV -saved value of GRAD
GRTONS -vehicle gross weight in tons
GRWT -vehicle gross weight in pounds
GUESS -calculated Y axis intercept in GUESS0
GWG -maximum gauge widening (inches)
GWMIN -minimum gauge widening effect on L/V
H -centre of gravity height of vehicle
HI -high rail wear (inches/MGT)
HILIF1 -high rail life

HILIF3 -high rail incremental life
HILIF5 -high rail marginal life
HILIFE -estimate life of high rail in years
HM -centre of gravity height of vehicle (S.I. units)
HP -horsepower per locomotive
HSAVE -saved value of H
HWHINC -high rail head wear of a specific vehicle (in/yr)
HWLINC -low rail head wear of a specific vehicle (in/yr)
I -counter
IAM -location of locomotive record in each direction
ICOUNT -counter used in GUESSO routine
ICWR -flag indicator for continuous welded rail (yes = 1, no = 0), in LOADER
IDIRN -direction of traffic (forward = 1, backhaul = 2)
IERRED -error flag (0 = no errors, 1 = errors present)
IFLAG -flag indicator, used in various routines
II -position of next lowest (further into the rail head) level in the stress concentration table
II1 -position of next highest (further into the rail head) level in the stress concentration table
IN -intermediate value in the look ahead line counter LINE
INAMES -character string in SPOT
INTERC -Y axis intercept of linear search routine GUESSO
IOFF -depth to look for fatigue (level number)
IPRINT -flag for optional print out in WR
IRUN -character string 'RUN' in SPOT
ISAVE -saved value of I
ISIGN -flag for sign of the exponent part of number in FREEIN
ITYPE -car type (locomotive = 1, freight car = 2, passenger car = 3)
IVAL -integer portion of number in free format reader FREEIN
IWAS -flag to indicate how WPR is to be used (design grade = 1, cars per loco = 2, value ignored = 3)
IWEAR -flag to indicate mode of wear calculation in WR (mechanical wear =1, batter =0)
IX -car number in array
J -counter
JJ -position of next lowest friction factor in stress concentration lookup table
JJ1 -position of next highest friction factor in stress concentration lookup table
JOIN -character string 'JOIN' of the word JOINTED
K -constant used in calculation of wheel rail contact geometry for contact stress determination
K1 -constant used in calculation of wheel rail contact geometry for contact stress determination
K1X -constant used in calculation of stresses into rail in CONCEN
K2X -constant used in calculation of stresses into rail in CONCEN
KEQ -equivalent spring constant for lumped rail and track mass
KH -linearized Hertzian contact stiffness
KPRIME -charge rate
KS -annual change rate for traffic type

KT -lumped equivalent track stiffness
L -track quality constant
L1 -factor for effect of gauge widening, lateral force on front axle in TRUCK (lbf)
L2 -factor for effect of gauge widening, lateral force on rear axle in TRUCK (lbf)
LAMBDA -track standard coefficient in VDYN
LASL1 -lateral slip on high rail by position (%)
LASL2 -lateral slip on low rail by position (%)
LASTP -flag for last print option turned on in print option string
LATOT -ratio of lateral force parallel to line between rail heads (lbs)
LATSL1 -lateral slip rate on high rail
LATSL2 -lateral slip rate on low rail
LF -lubrication factor (ratio fo friction factor to limiting friction factor)
LIFE -life in MGT
LINES -number of lines in look ahead line counter LINE
LMTSTS -transitional stress between mild and severe wear
LN -number of locomotives
LO -low rail wear (inches/MGT)
LOLIF2 -low rail life
LOLIF4 -low rail incremental life
LOLIF3 -low rail marginal life
LOLIFE -estimate of low rail life in years
LONSL1 -longitudinal slip rate on high rail
LONSL2 -longitudinal slip rate on low rail
LOOP -counter for run number
LOSL1 -longitudinal slip on high rail by position (%)
LOSL2 -longitudinal slip on low rail by position (%)
LOV -lateral to vertical force ratio before taking into consideration the effects of superelevation, coupler loads and gradient
LOV1 -LOV on leading axle in TRUCK
LOV2 -LOV on trailing axle in TRUCK
LOVNEW -L/V ratio with consideration of offbalance,buff loads and gradient
LOVSAV -saved value of L/V ratio for first axle position
LPC -locomotives per consist
LU -character string 'LU' of the word LUBRICATED
LUBNAM -variable name of character string 'UNLU' or 'LU' for the word LUBRICATED
LUBRIC -lubrication flag (1 = yes, 0 = no)
LVNEW -array of L/V's by axle and position
M -total mass of car (S.I. units), track mass in VDYN
MAXLF -maximum life of rail under no wear conditions
MCYCAL -maximum cycles for SN curve
ME -effective track mass (kg)
MILD -flag for mild wear ('m')
MINER -Palmgren - Miner criterion
MOARM -moment arm length used fo calculate offloading by locomotive traction (inches)
MR -mass of rail (lbs per foot)

```
MT        -mass of ties (lbs of half tie per foot)
MT1       -lumped equivalent track mass (ks)
MU        -unsprung mass per wheel (ks)
MUEMAX    -limiting friction factor (between wheel and rail under dry,
           unlubricated conditions)
MUT       -intermediate value (MU + MT1) in LOCO
N         -number of locomotives in LOCO
NAME      -character string in WR
NAMECF    -name of calibration file
NAMEDK    -name of scratch file
NAMELP    -name of line printer
NAMER     -character string for 'RAIL WEAR:  RAIL BATTER:'
NAMERD    -name of reader
NAMES     -array storage of variable names in SPOT
NAMEST    -name of stress tables
NAMETT    -name of screen
NAXLE     -number of axles per truck by vehicle
NCARD     -input card number
NCARS     -number of cars by direction (NCARS(1) forward, NCARS(2) back-
NCARS     -haul)
NEXT      -counter in FREEIN
NF        -number of friction coefficients in CONCEN table
NFC       -number of friction coefficients in array FC, equal to NF in
           CONCEN
NL        -numbers of levels in stress concentation table
NLD1      -normal force on high rail (lbf)
NLD2      -normal force on low  rail (lbf)
NLDALL    -array storge of normal force by rail position in CAR
NLOAD1    -normal force on high rail (lbf)
NLOAD2    -normal force on low  rail (lbf)
NNAME     -number of data names in input data file
NONE      -character string ' '
NOW       -intermediate value in LINES
NUM       -total number of cars in both directions in SCLMGT
NVAR      -variable number in string on data card
NWRD      -word number in CALFIL, number of floating point variables
NWRD      -in value in FREEIN, new output word in FREEIN
NX        -array of NCARS by direction
NZS       -number of levels in stress concentration table, equal to NL
           in CONCEN
OFF       -depth to look for fatigue (level number),offbalancing effect
           in XLOVRT
OFFB      -off balance effect in XLOVRT by car or truck type
OFFBAL    -part of total lateral load acting to increase L/V (0 - .5)
ONE       -contested one in the bending moments
OUTP      -array of output flags
OVERR     -one over the raduis of curvature (1/ft)
P         -contact load (N)
P1        -high frequency impact force, P1 (lbf)
P1M       -estimate of P1 force during iteration in VDYN (N)
P1MNEW    -new estimate of P1 force during iteration in VDYN.
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```
P2       -low frequency rebound force, P2 (lbf)
P2M      -P2 force (N)
PERM1    -calculated total high rail  wear in inches/100MGT
PERM2    -calculated total low rail   wear in inches/100MGT
PERM3    -calculated total gauge face wear in inches/100MGT
PHF      -high frequency load due to rail surface irregularities
PHI      -difference between actual stress and threshold stress,if > 0.0
          plastic flow exists
PHIALL   -stores all friction factor (PHIALL(*,1) unlubricated,
          PHIALL(*,2) lubricated)
PHIF     -array storage of PHF by axle and position
PHIMX1   -friction factor on high rail head
PHIMX2   -friction factor on low  rail head
PHIMXF   -friction factor on high rail flange
PHIP     -rail degradation due to plastic flow
PHIPB    -plastic flow due to batter at joints or welds
PHIPFF   -array storage for plastic flow on low rail head due to false
          flange contact
PHIPSV   -saved value of PHIP
PHIS     -abrasive wear rate on rail
PHISB    -abrasive wear rate due batter loads at joints or welds
PHISFF   -array storage for abrasive wear rate on low rail due to false
          flange contact
PHISSV   -saved value of PHIS
PIP      -array storage for PHIP by axle and position in FF
PIS      -array storage for PHIS by axle and position in FF
PLF      -low frequency dynamic load due to rail surface irregularities
PLOF     -array storage of PLF by axle and position
PO       -wheel load (lbs)
POIS     -Poisson's ratio (for steel: 0.30)
POM      -wheel load (N)
POM66    -intermediate value
PONE     -array storage for P1
POSAVE   -saved value of PO
POSI     -axle position indicator (1 front, 2 rear, 3 middle)
POWER    -power required for train in LOCO  (horsepower)
POWPL    -horsepower per locomotive required by locomotive to overcome
          it's own resistance (horsepower)
PP       -contact load (lbs)
PRTOUT   -output file number
PTWO     -array storage for P2
PW       -power required for train in LOCO (tons x mph)
QQN      -friction factor
QQNALL   -array of friction factors by location
QQQN     -array of friction factors by axle and location
QX       -probability of false flange contact on low rail
QXFF     -array of QX by axle
R        -raduis of wheel for vehicle in meters
R3       -wheel raduis (inches)
RATIO    -cycle ratio, ratio of wheel radii in CREEP
RBACK1   -cycle ratio last time stop
```

RDEPTH -depth per layer into rail head for stress concentrations estimation (inches)
READER -input file number
RESIST -resistance of locomotive in TRAIN
RESUL2 -minimum contact stress in rail by level and friction factors
RESULT -maximum contact stress in rail by level and friction factors
RHI -maximum wheel radius
RI -cross section rail inertia (lbf/in/in)
RL -total rolling resistance of locomotives in lbf
RLO -minumum wheel radius
RM -currently not used
RO -dip joint support factor
ROK -return on investment (default = 15%)
RR -total rolling resistance of cars in lbf
RSAVE -saved value of R
RSTIFF -rotational stiffness of track
RUNID -run identification label
RUNOUT -acceleration of car due to runin/runout
RVCOST -replacement value cost of rail (new cost - salvage value)
S -half the gauge
SALV -salvage value per mile, (default = $33,000)
SAMP -amplitude stress in fatigue analysis based on maximum and minimum stress
SAVBT1 -saved value of SUMBT1 in the tonnage scaling calculations in PASS2
SAVBT2 -saved value of SUBBT2 in the tonnage scaling calculations in PASS2
SAVCAR -common block containing saved values of the car parameters
SAVES -intermediate value of slip or creep in WEARMD
SAVGF -saved value of SUMGF in PASS2
SAVHI -saved value of SUMHI in PASS2
SAVLO -saved value of SUMLO in PASS2
SAVMGT -saved value of SUMMGT in PASS2
SCALE -scaling factor to remove marginal traffic from total in PASS2 equal to (XMARGN/XMGT), scale factor for L/V in XLOVRT
SCOS -length of horizontal projection of rail gauge with superelevation SE
SDFAC -standard deviation of forces by axle (SDFAC(1) front, SDFAC(2) rear, SDFAC(3) middle)
SE -superelevation in inches (SE = -1 , balanced superelevation)
SECAL -endurance limit ratio to BHN
SEGOOD -effective applied stress as calculated by modified Goodman diagram
SELECT -contact location indicator (1 high rail head, 2 low rail head, 3 high rail gauge face)
SEM -superelevation (S.I. units)
SEO -endurance limit under static load conditions (considered to be 0.9 x ultimate strength)
SESAV -saved value of SE
SEVER -flag for severe wear ('s')
SEX -endurance limit of rail

SFANG -sine of flange angle
SHEARK -shear stength of rail steel
SICP -array storage of SIGCP by position and axle in WR
SICPFF -array storage of SIGCP by position in FF
SIGCP -maximum stress on contact patch (lbf/in x in)
SIGMAX -maximum stress into rail (initialized at -1.E32)
SIGMIN -minimum stress into rail (initialized at 1.E32)
SIGN -value used to provide the proper sign for gradient after grade compensation, sign of number in FREEIN (positive = 1, negative = 2)
SIGX -stress at a given level into the rail
SINTH -sine of vertical angle due to superelevation
SL -rail lives in years
SLICE -step size in inches for fatigue calculations
SLIPFH -horizontal flange slip
SLIPFL -lateral flange slip
SLIPFV -vertical flange slip
SLIPX -horizontal slip on flange (Z)
SLIPY -lateral slip on flange (Z)
SLIPZ -vertical slip on flange (Z)
SLOPE -calculated slope between points in linear search GUESS0
SMAX -maximum stress in rail, SMAX in CYCRAT equivalent to RESULT in CONCEN
SMEAN -mean stress in rail
SMIN -minimum stress in rail, SMIN in CYCRAT equivalent to RESUL2 in CONCEN
SPAN -distance between front axle and rear axle in truck (inches)
SPD -design speed
SPDWT -weightings for speeds used in TDOP summaries
SQR -intermediate value in stress concentration calculation in CONCEN - square root of (K2X/K1X)
STATE -flag indicating false flanging
STDEV -standard deviation of lateral forces
STORE -array which saves values for linear earch in GUESS0 (STORE(1) longitudinal slip, STORE(2) sum of torques, STORE(3) slope of line between last guess and this guess)
STRESS -file containing stress concentration tables
STRING -character string used in FREEIN
STRMAX -maximum stress as determined from applied stress environment
STRMIN -minimum stress as determined from applied stress environment
STRNG -character string used in FREEIN
SUBT -constant used in calculation wheel/rail geometry for contact stress determination
SUCAL -ultimate stress ratio to BHN
SUM -cycle count limit
SUMBT1 -total batter wear in inches/year on high rail
SUMBT2 -total batter wear in inches/year on low rail
SUMGF -total gauge face wear in inches/year
SUMHI -total high rail tread wear in inches/year
SUMLO -total low rail tread wear in inches/year
SUMMGT -total million gross tons traffic as steps through traffic

SUMX -wear in inches/year in FATLIF (equals SUMHI or SUMLO)
SUT -ultimate strength of steel
SWCAL -severe wear threshold calibration
SWINC -side wear per vehicle type
SX -scale factor for lateral force by car or truck type in XLOVRT
T -intermediate value in calculation of probability of false flange
T1 -intermediate value in calibration of stresses into rail in CONCEN
T2 -intermediate value in calibration of stresses into rail in CONCEN
T3 -intermediate value in calibration of stresses into rail in CONCEN
T4 -intermediate value in calibration of stresses into rail in CONCEN
T90 -90 degrees minus THETA, used in determination of constants for contact patch dimension calculation
TED -character string 'TED' of the word JOINTED
TEMP -difference between ultimate strength of rail steel and mean stress
TEMP1 -vertical component of friction at flange contact
TEMP2 -lateral component of friction at rail head contact
TEN -fractional part of value in FREEIN
TERM1 -factor for stresses due to distributed normal forces in CONCEN
TERM2 -factor for stresses due to distributed tangential forces in CONCEN
TEST -threshold between mild and severe wear
TF1 -total force magnitude at high rail (lbf), TOTFOR by axle and position
TF2 -total force magnitude at low rail (lbf), TOTFOR by axle and position
TFANG -tangent of flange angle
TFF -total force magnitude at flange (lbf), TOTFOR by axle and position
THET -track tilt angle due to superelevation (radians)
THETA -angle used in calculation of contact patch size (inches)
THOLD -storage array for TOLD by axle and position in FF
THRSCL -plastic flow threshold calibration
TIME -rail life in years, used in discounting calculations in COSTS
TIMES -scaling factor for tonnage (TOTMGT/SUMMGT)
TMW -total mechanical wear (inches)
TMWBAT -total mechanical wear due batter at joints and welds
TMWFF -array storage of total mechanical wear due to false flange contact on low rail gauge (inches)
TODAY -date character string
TOICST -average incremental charge assuming uniform distribution of rail lives (cents/1000 ton-miles)
TOLD -threshold stress at which plastic flow will occur in a rail
TOLDB -threshold stress for plastic flow at joints and welds
TOLDFF -array storage of TOLD under conditions of false flange contact
TOMCST -average marginal charge assuming uniform distribution of rail lives (cents/1000 ton-miles)
TONS -vehicle gross weight in tons
TORQ1 -torque at high rail head contact
TORQ2 -torque at low rail head contact
TORQF -torque at high rail flange contact about moment arm
TOSL1 -total slip on high rail (%)

```
TOSL2   -total slip on low  rail (%)
TOSLF   -total slip on flange    (%)
TOT     -new total tonnage without locomotives, for rescaling in SCLMGT
TOT2    -new total tonnage  with   locomotives, for rescaling in SCLMGT
TOTALL  -total slip on high rail by axle and position
TOTFOR  -total force magnitude
TOTMGT  -total million gross tons
TOTSL1  -total high rail slip
TOTSL2  -total low  rail slip
TOTSLF  -total   flange  slip
TR      -total rolling resistance
TRAM    -tramming angle (radians)
TRL     -maximum lateral irregularity in inches
TRMOLD  -vehicle force due to torque on wheel (lbf) - traction off-
          loading effect on the axles of a locomotive
TRMSLP  -tram slope with car weight (theory = 0.0)
TRMSTF  -tram stiffness
TRV     -maximum vertical irregularity in inches
TSTIFF  -tramming stiffness
TW      -total weight of vehicle (S.I. units)
TWA     -transposal wear allowance (default = 0.75)
TYPE    -car type (locomotive = 1, freight car = 2, passenger = 3)
TYPSAV  -saved value of TYPE
U       -track modulus in lbf/in/in
UCOST   -replacement cost per mile of track, (default = $127,000)
UNLU    -character string of 'UNLU' of the word UNLUBRICATED
V       -speed of traffic class (mph)
V00     -factor for making linear interpolation of stress table based
          on actual friction and depth into rail
V01     -factor for making linear interpolation of stress table based
          on actual friction and depth into rail
V10     -factor for making linear interpolation of stress table based
          on actual friction and depth into rail
V11     -factor for making linear interpolation of stress table based
          on actual friction and depth into rail
VALUE   -value of number decoded in FREEIN
VAR     -parameter used in calculation of bending moments, a function
          of wheel load, E, RI and U
VARS    -ASCII variable names preceeding each value in FREEIN
VEHNAM  -character string for truck type label
VM      -speed (S.I. units)
VSAVE   -save value of V
W       -slip or creep rate in WEARMD
WEARRAT -ratio of rate of plastic flow to ratio of abrasive wear
WEARSM  -array storage of TMW's by axle and location (inches)
WEARTT  -array storage of wear sums for car type by cuntact location
          (inches/MGT)
WLIFE   -rail wear life in years
WLIFEC  -rail wear life in cars of class
WLIFEM  -final wear life in MMGT
WNEW    -sum of vertical forces on high rail in torque balance
```

WNR -natural frequency of track, based on track modulus and rail mass
WORD -temporary storage location for reading in data, floating point number in value in FREEIN
WORKHD -work hardening (WORKHD(1,*) work harding scale, WORKHD(2,*)
WORKHD maximum curvature, WORKHD(*,1) on high rail, WORKHD(*,2) on low
WORKHD rail, WORKHD(3,*) on gauge face)
WPR -weight to power ratio (tons/loco), cars per locomotive, design grade
WRABR -scale factor for abrasive wear
WRAT -array storage of WEARAT by axle and position in FF
WRATFF -array storage of WEARAT by position in FF
WRPLS -scale factor for plastic deformation
WUE -unsprung weight per wheel
WUESAV -save value of WUE
X -position along rail from contact patch in stress concentration table, rear axle position away from centre in TRUCK (inches), x position in linear search GUESSO, number of standard deviations from critical lateral force for false flange contact
XA -length of longitudinal semi-axis of contact patch
XAB -square root value of XAPLSB squared plus XBLESA squared in calculation of contact patch size
XAPLSB -A + B in calculation of contact patch size
XB -length of lateral semi-axis of contact patch
XBLESA -A - B in calculation of contact patch size
XK -constant determined by steel properties POIS and E for contact patch calculation
XLIFE -fatigue life in years
XLIFHI -high rail fatigue life years
XLIFLO -low rail fatigue life years
XLOAD -wheel load in lbf-ft in CYCRAT
XLONG -constant used in final calculation of contact patch major semi-axis
XMARGN -million gross tons to base marginal cost calculations on
XMGSAV -save value of XMGT
XMGT -annual million gross tons of car class (before scaling to TOTMGT)
XNEUT -distance from top of rail to neutral axis
XNOW -value of X coordinate linear search routine GUESSO
XOVERA -X divided by A in CONCEN
XR1 -wheel radius in contact stress calculation, equals R3 (inverted for calculation)
XR11 -lateral wheel curvature at contact location in contact stress calculation, equals CW(*) (inverted for calculation)
XR1M11 -intermediate value used in calculation of contact patch size
XR22 -lateral rail curvature at contact location in contact stress calculation, equals CR(*) (inverted for calculation)
XSHORT -constant used in final calculation of contact patch minor semi-axis
XSQ2 - times X squared in CONCEN
XSTIFF -rear axle position stiffness for truck (lb/in)

XX - axle position along rail relative to contact location used for calculation of maximum bending moment times BETA, in CONCEN, proportion of distance between next highest and next lowest depth in stress table the effective depth Z/A exceeds next lowest depth in CYCRAT

XX1 - axle position along rail relative to contact location used for calculation bending moment times BETA

XX2 - axle position along rail relative to contact location used for maximum bending moment for 2 axle car, minimum bending moment for 3 axle car times BETA

XX3 - axle position along rail relative to contact location used for calculation bending moment times BETA

XX4 - axle position along rail relative to contact location used for calculation bending moment times BETA

XX5 - axle position along rail relative to contact location used for calculation bending moment times BETA

XXMAGN -20 times XMARGN

XXX - intermediate value which is scaled to get values of minor and major semi-axes of contact patch

Y - lateral position of axle in inches, y position in linear search routine GUESSO, distance from level in rail head to neutral axis of rail in CYCRAT (inches)

Y1 - equilibruim position on wheel tread for front axle (inches)

Y2 - equilibruim position on wheel tread for rear axle (inches)

YMAX - distance between axles (inches)

YMU - lateral force as determined from the L/V ratio for the axle

YNOW - value of Y coordinate in linear search routine GUESSO

YS - lateral position of axle

YY - in stress concentration table lookup proportion of difference between next lowest and next highest friction exceeds next lowest in table

YY1 - in stress concentration table lookup proportion of difference between next lowest and next highest friction is less than next highest in table

Z - distance into surface of rail stress applied in CONCEN

ZERO - variable name for 0.

ZETX1 - constant used in calculation of stresses in rail head in CONCEN

ZETX2 - constant used in calculation of stresses in rail head in CONCEN

ZETX2

ZOVERA - Z divided by A in CONCEN and CYCRAT - factor for choosing appropriate maximum and minimum stress out of stress tables (depth

ZOVERA divided by contact patch area)

ZOVERA

ZS - equals Z

ZSQ - Z squared

ZSQ2 - 2 times Z squared

APPENDIX B

PROGRAM LISTING

A full listing of the Rail Wear Cost Model computer program is available with purchase of the model from CIGGT. Inquiries should be made to:

Canadian Institute of Guided Ground Transport
Goodwin Hall, 6th Floor
Queen's University
Kingston, Ontario, Canada
K7L 3N6

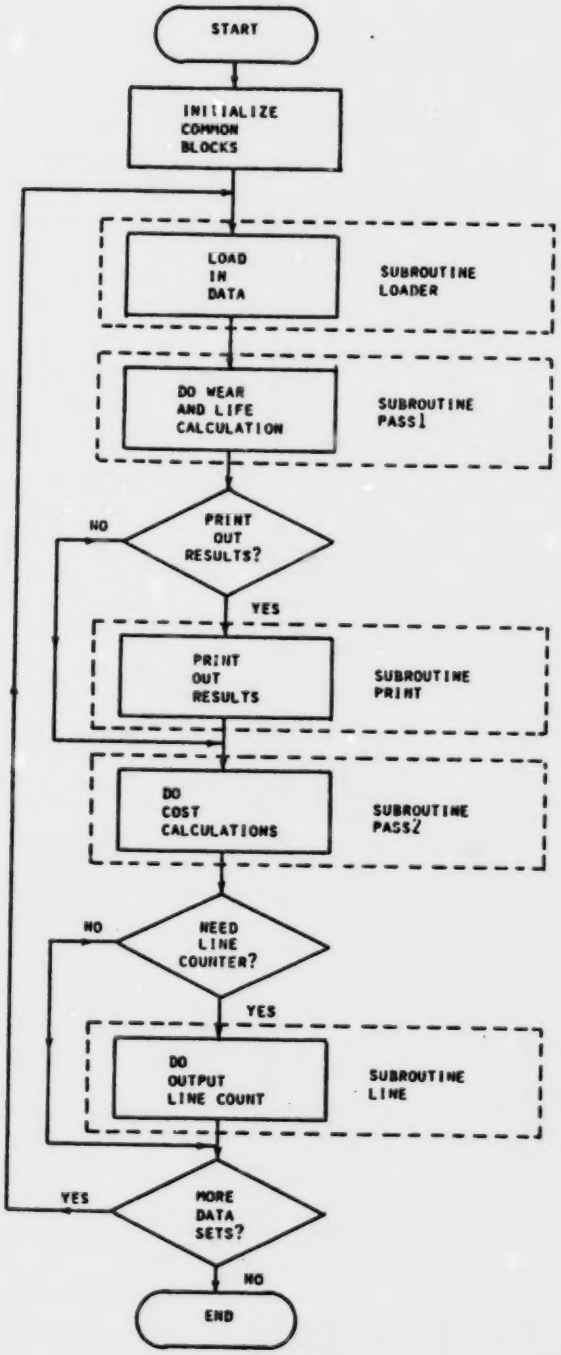
(613) 547-5777

APPENDIX C

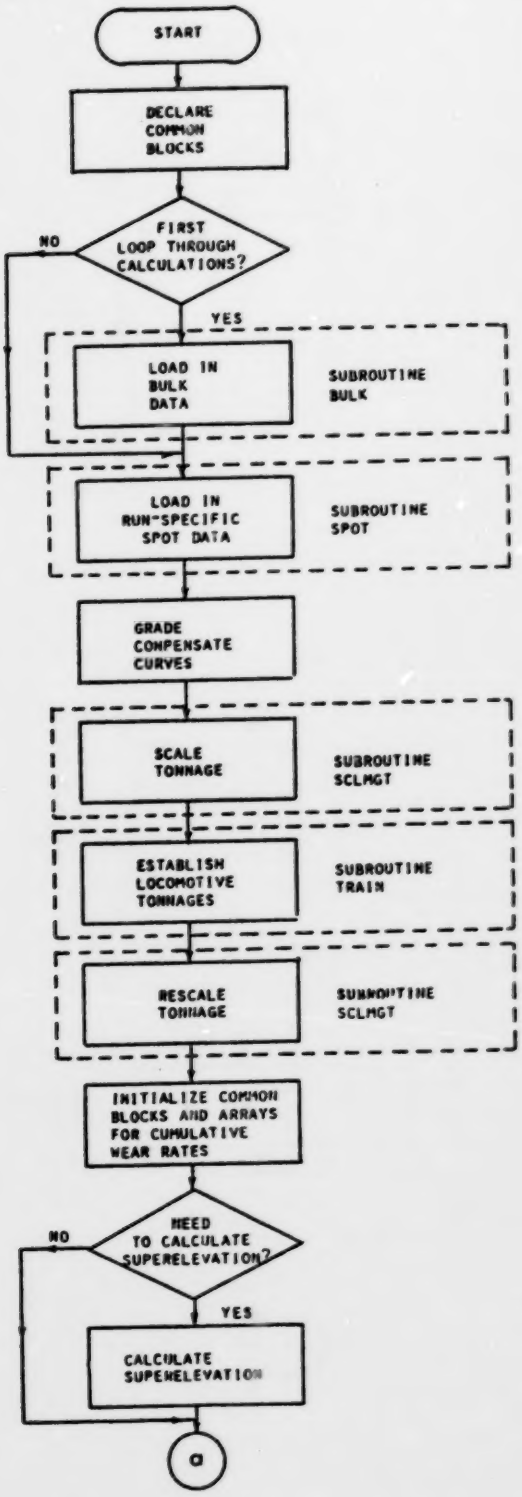
PROGRAM FLOWCHARTS

Subroutine ROOT
Subroutine LOADER
Subroutine BULK
Subroutine CALS
Subroutine CONCEN
Subroutine SPOT
Subroutine SCLMGT
Subroutine TRAIN
Subroutine LOCO
Subroutine LINE
Subroutine FREEIN
Subroutine PASS1
Subroutine VEHIN
Subroutine CAR
Subroutine ACTIVE
Subroutine VERT
Subroutine XLOVRT
Subroutine DELTA
Subroutine TRUCK
Subroutine CREEP
Subroutine GUESSO
Subroutine VDYN
Subroutine REVCON
Subroutine WR
Subroutine CNSTRS
Subroutine WEARMD
Subroutine CYCRAT
Subroutine LIFE
Subroutine PASS2
Subroutine FT
Subroutine FATLIF
Subroutine COSTS
Subroutine PRNT

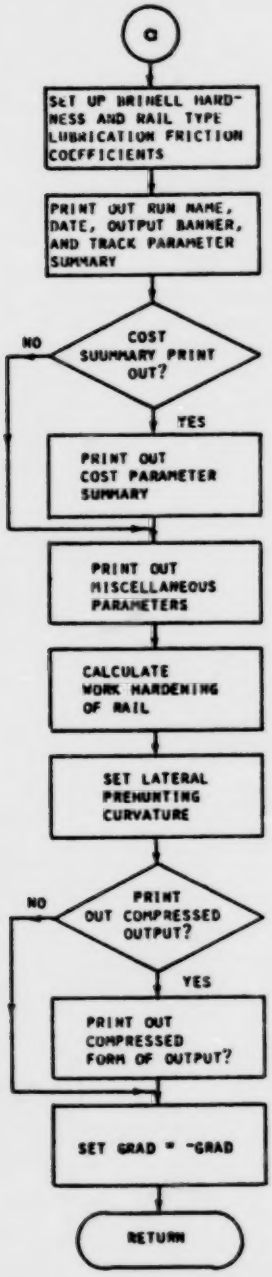
Subroutine ROOT



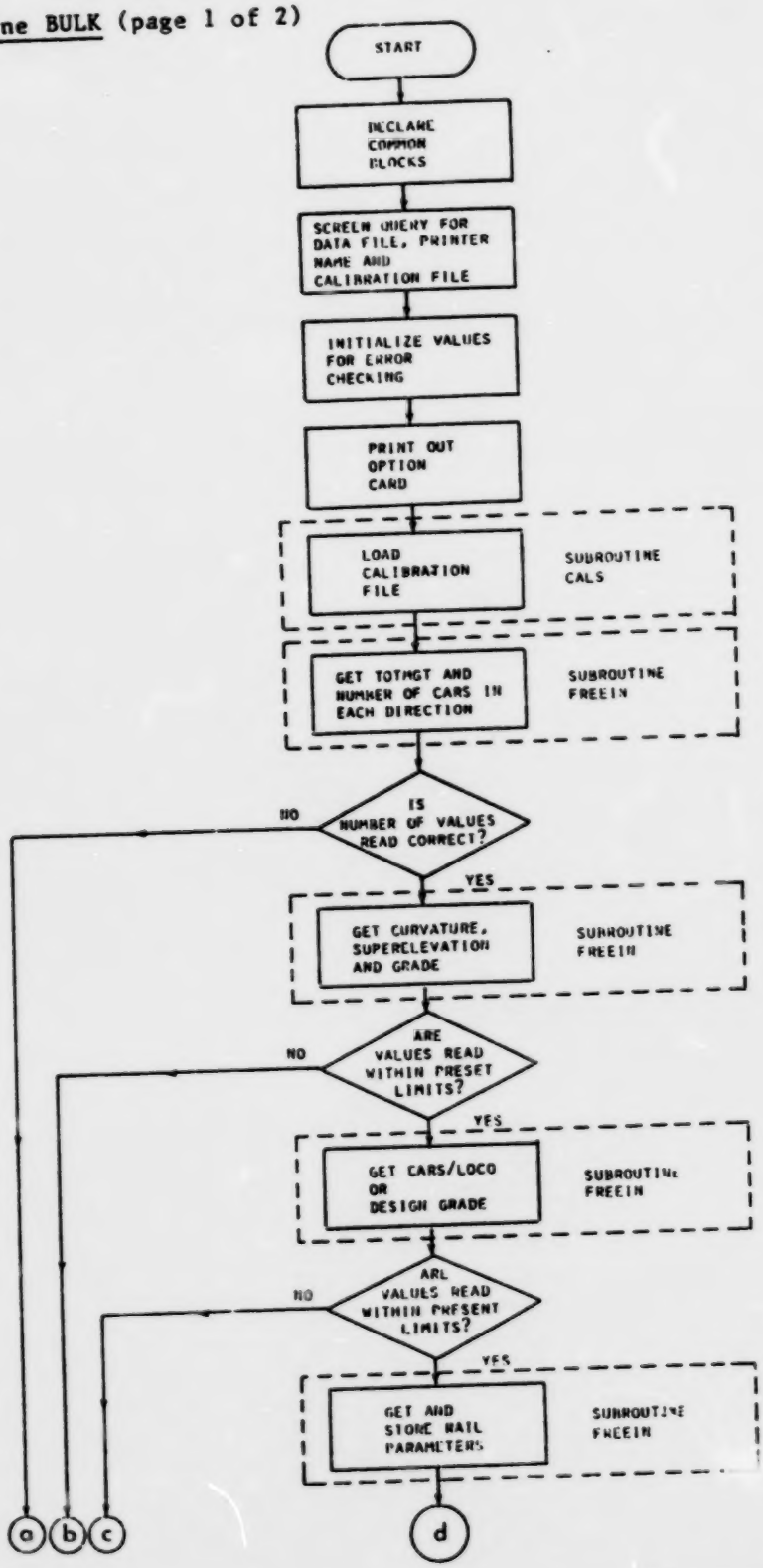
Subroutine LOADER (page 1 of 2)



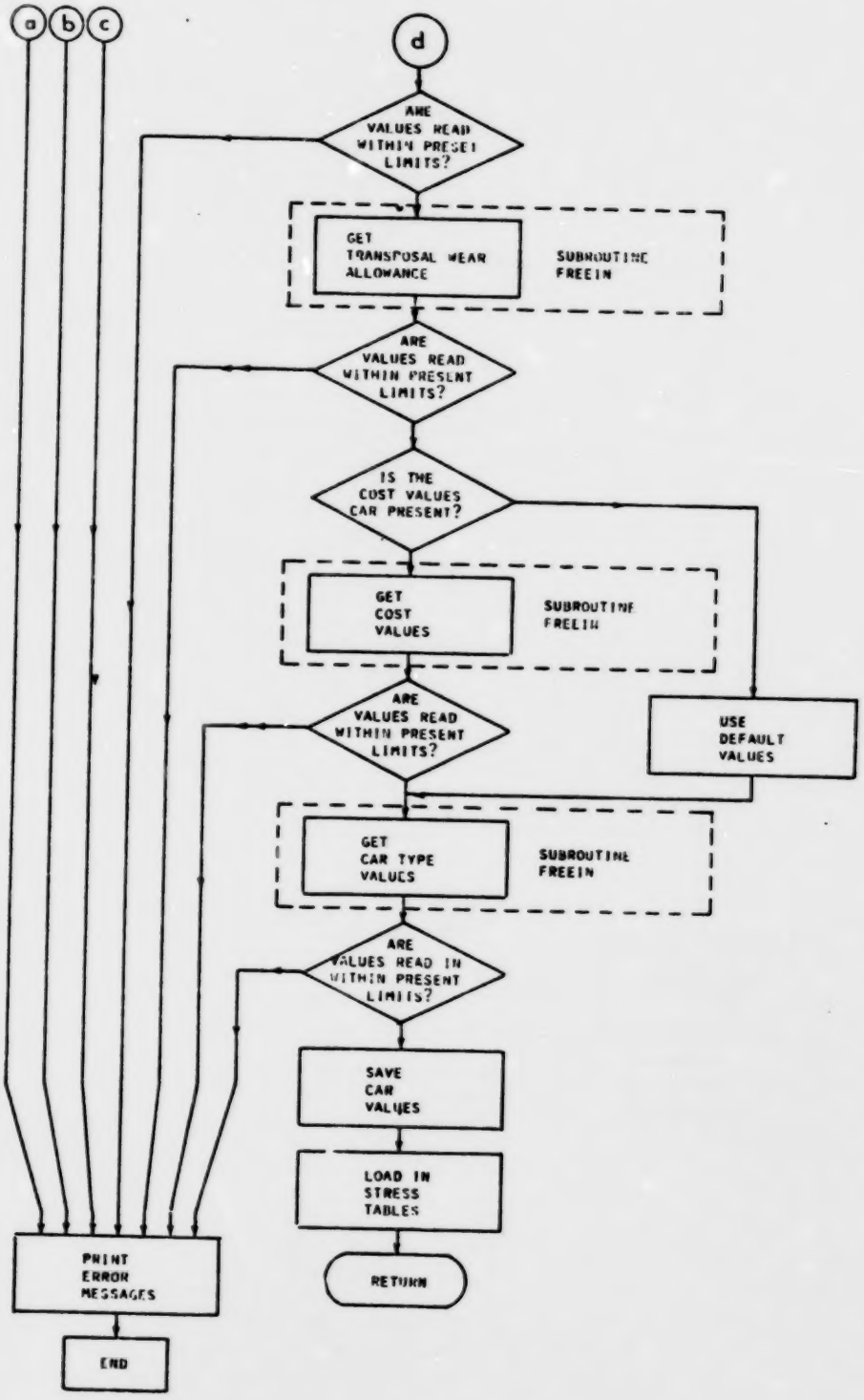
Subroutine LOADER (page 2 of 2)



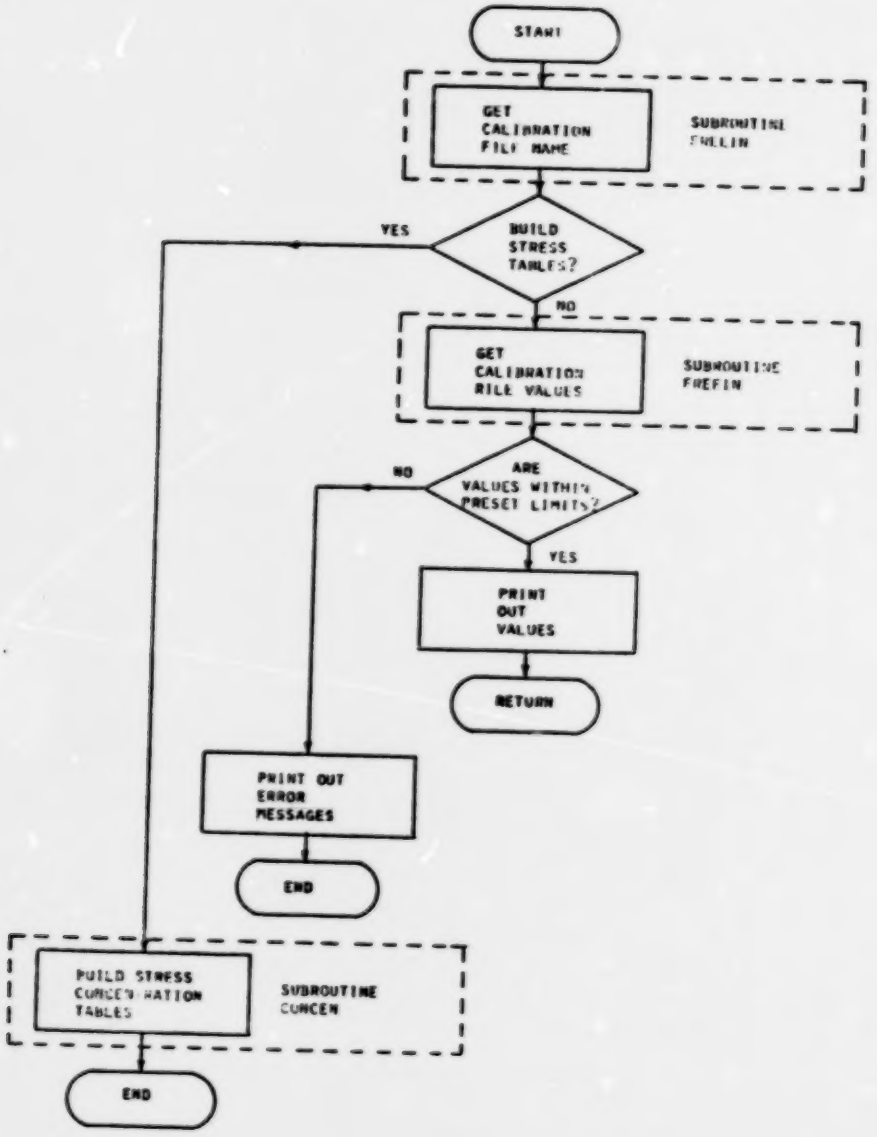
Subroutine BULK (page 1 of 2)



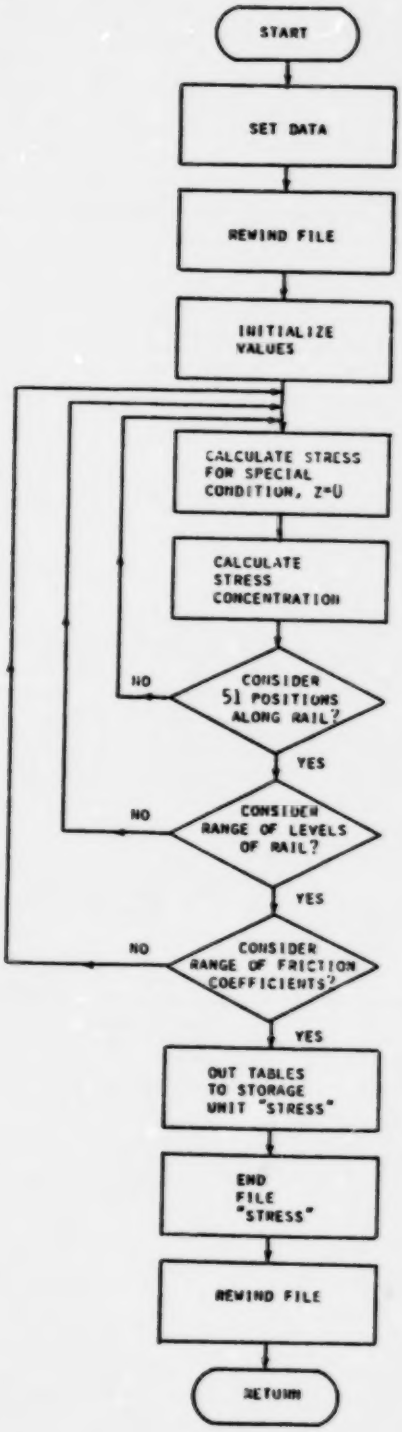
Subroutine BULK (page 2 of 2)



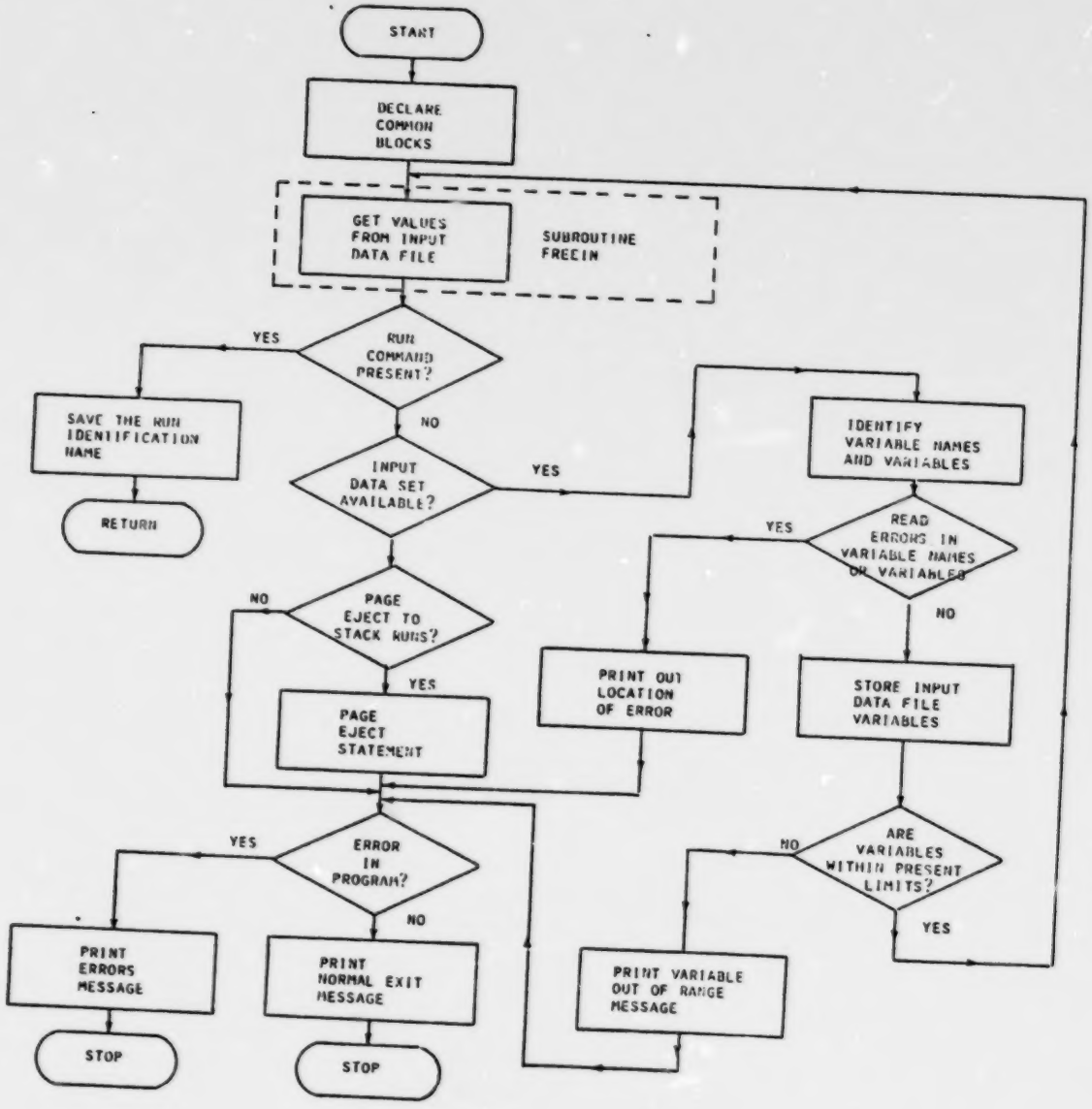
Subroutine CALS



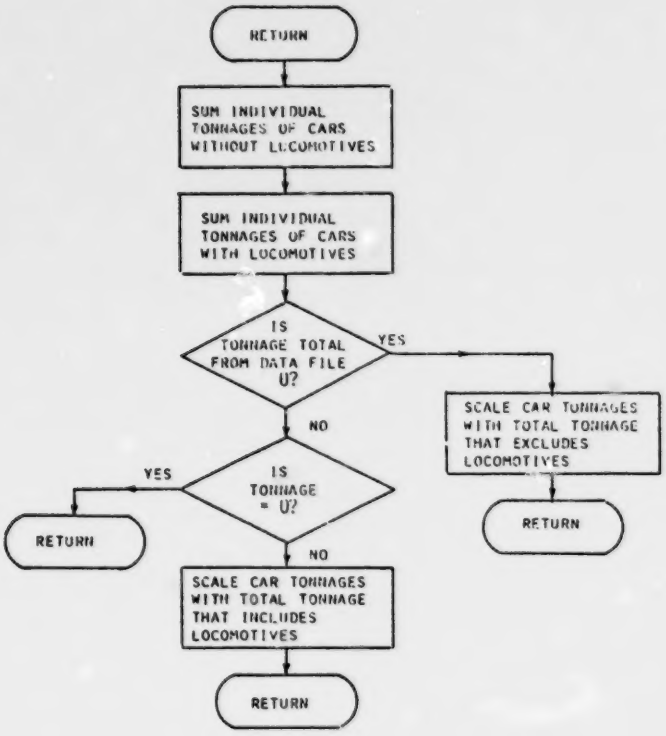
Subroutine CONCEN



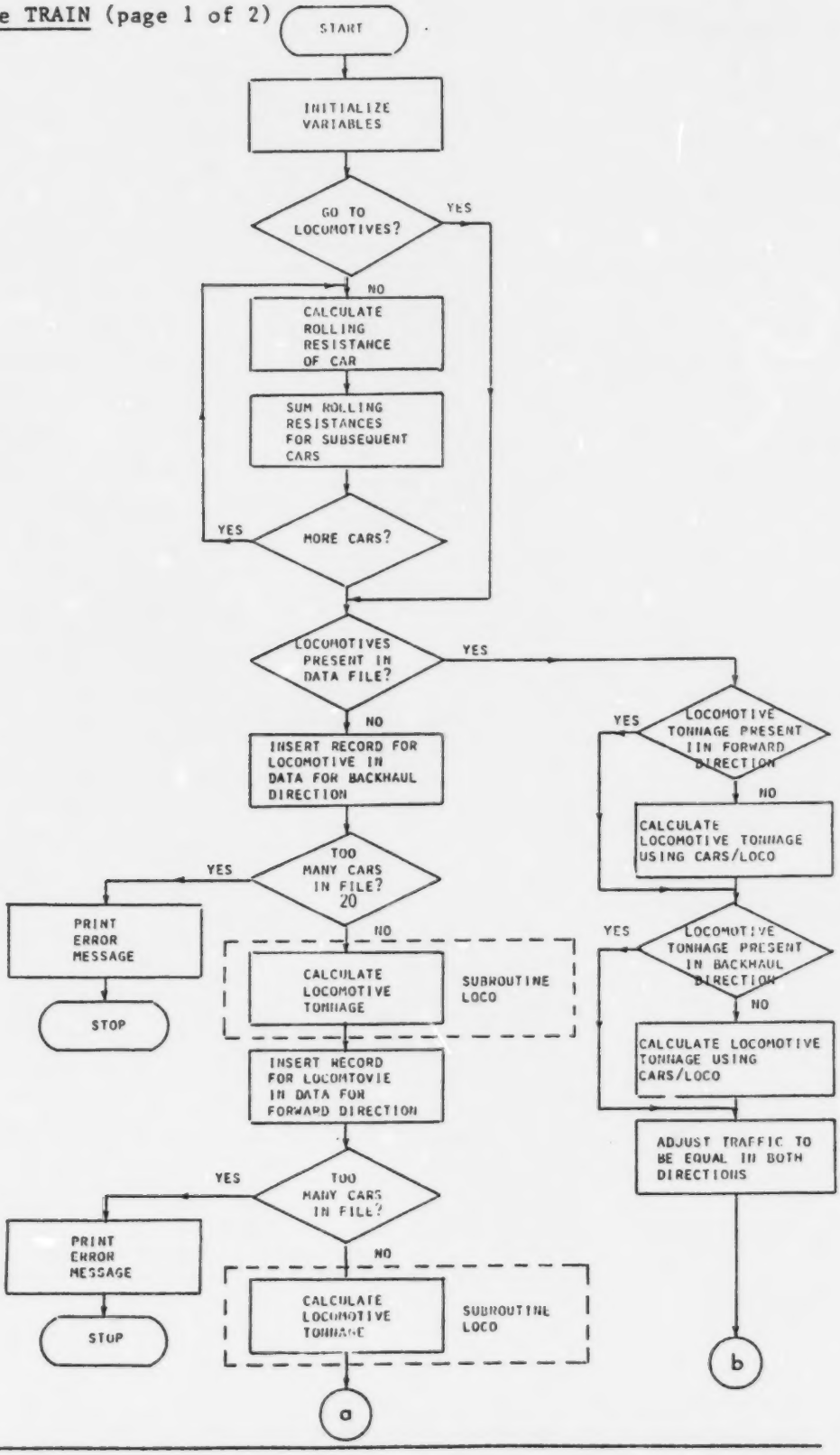
Subroutine SPOT



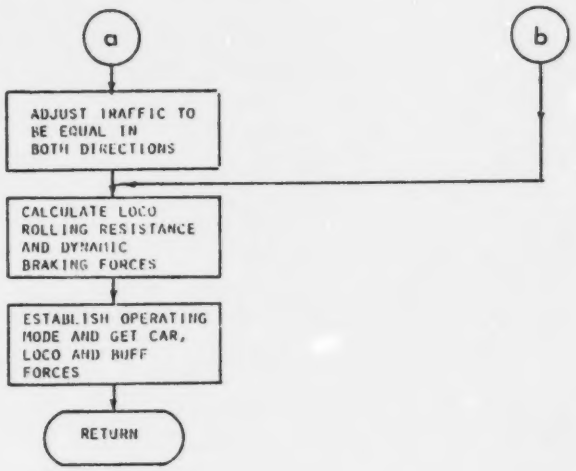
Subroutine SCLMGT



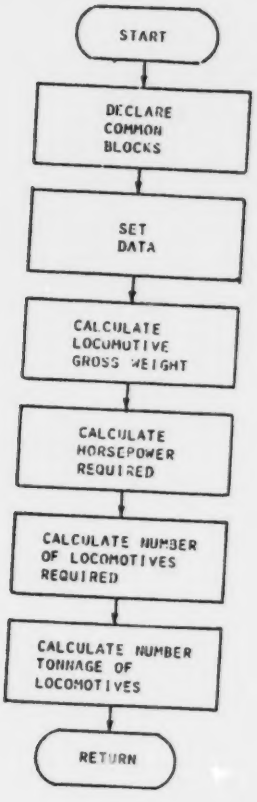
Subroutine TRAIN (page 1 of 2)



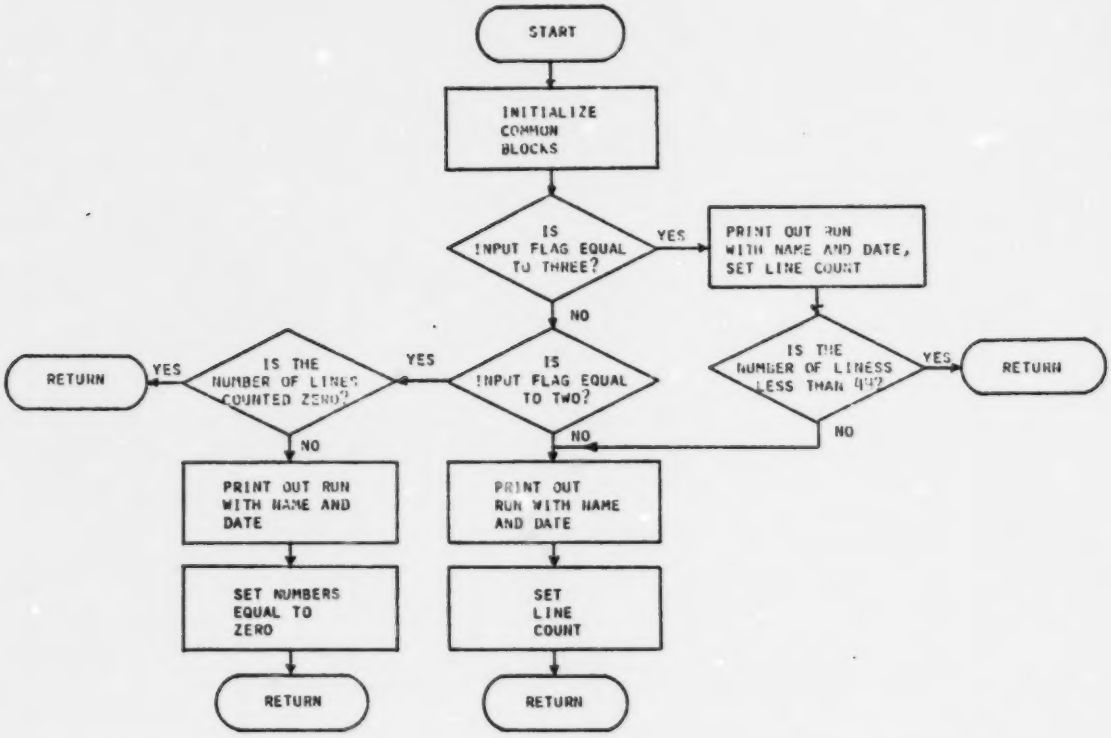
Subroutine TRAIN (page 2 of 2)


a
b
ADJUST TRAFFIC TO BE EQUAL IN BOTH DIRECTIONS
CALCULATE LOCO ROLLING RESISTANCE AND DYNAMIC BRAKING FORCES
ESTABLISH OPERATING MODE AND GET CAR, LOCO AND BUFF FORCES
RETURN

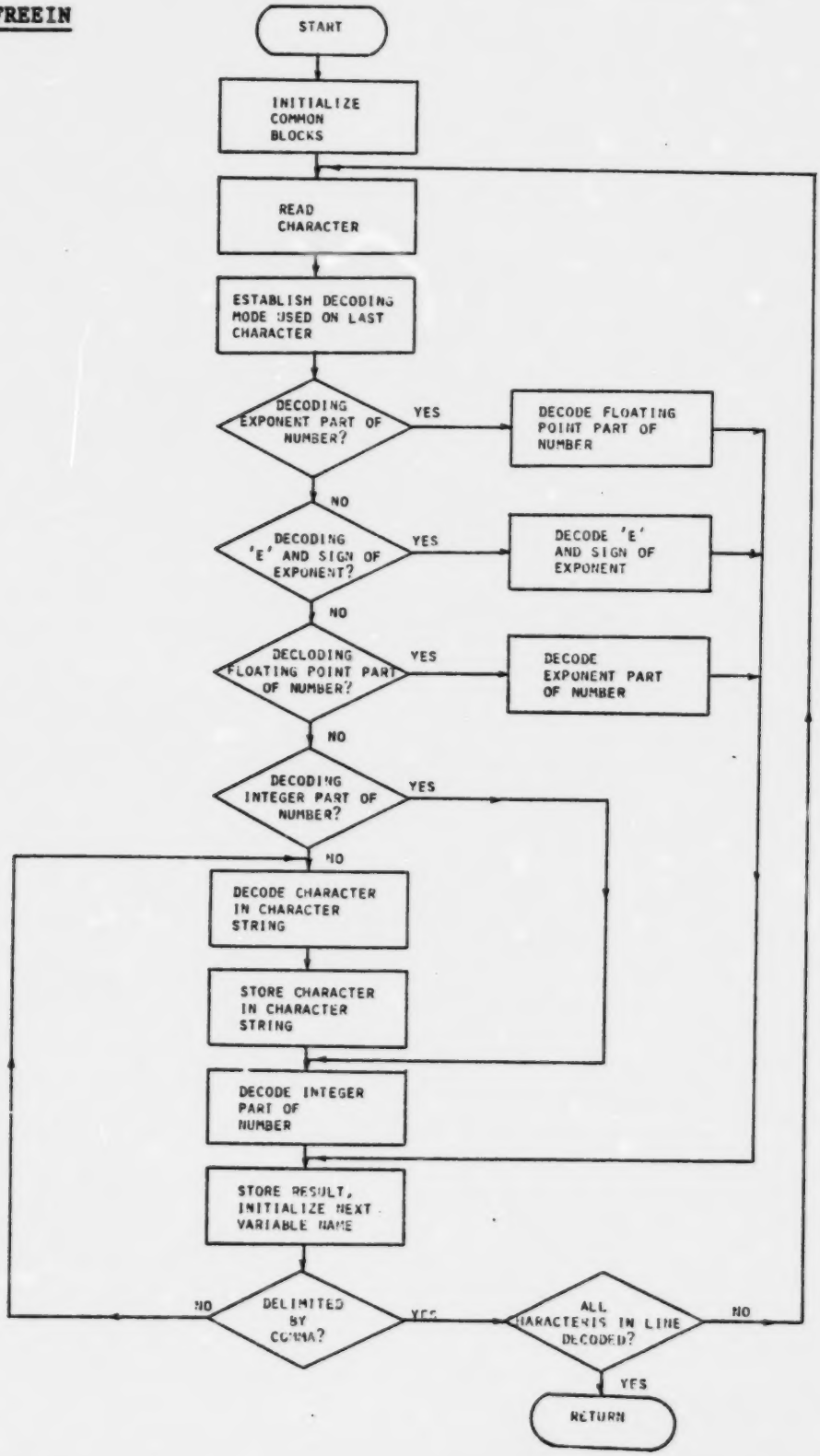
Subroutine LOCO



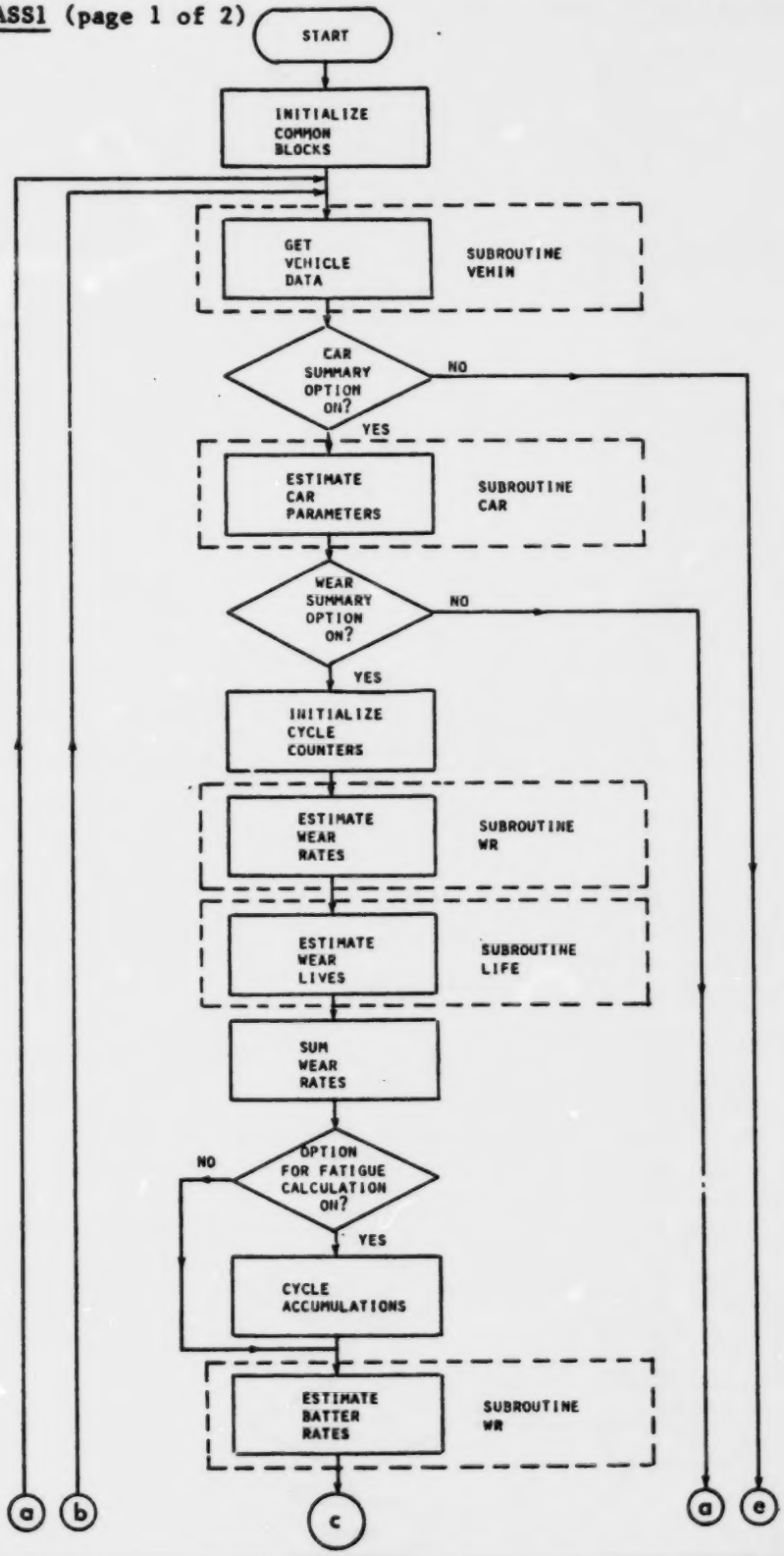
Subroutine LINE



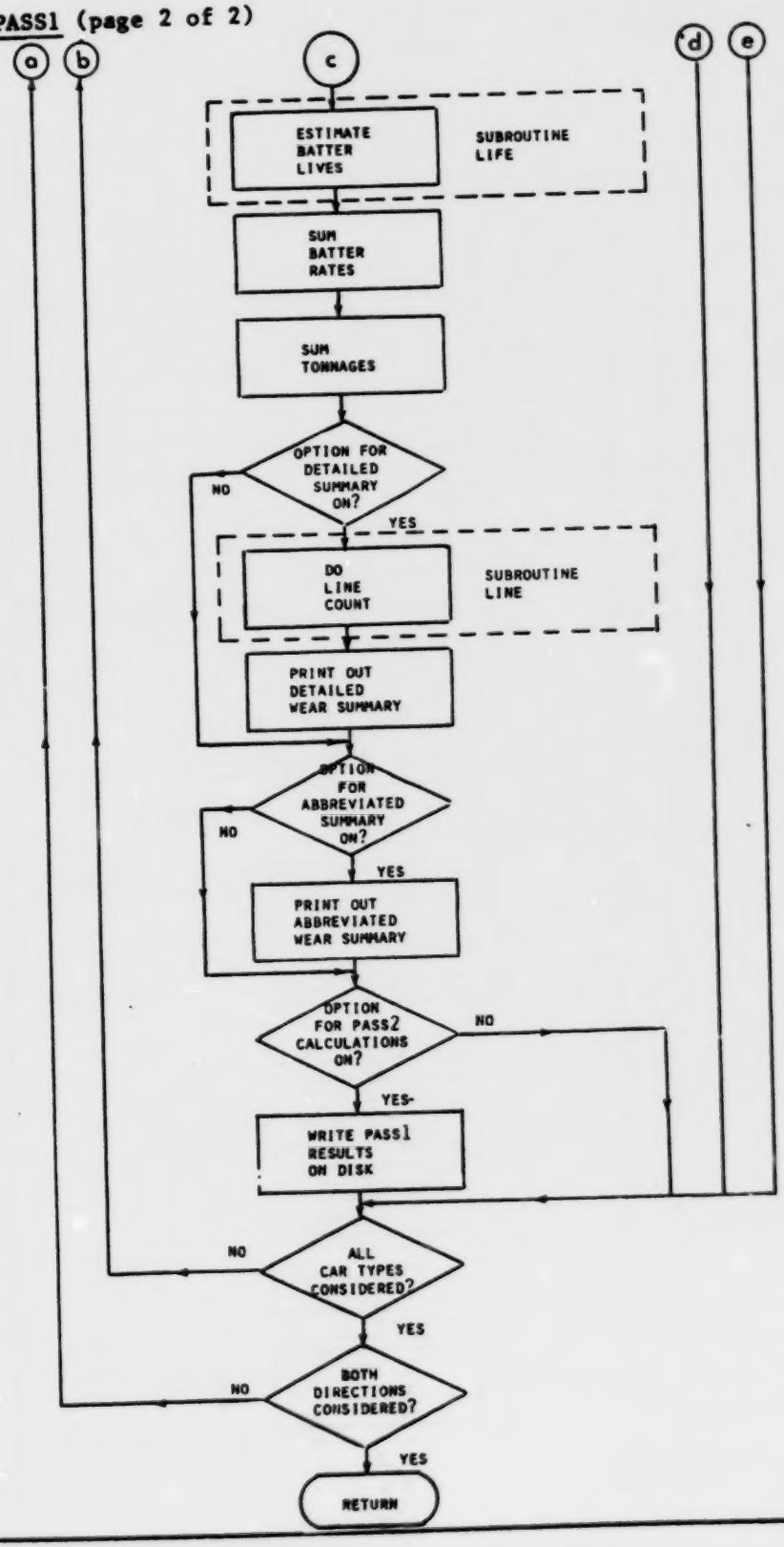
Subroutine FREEIN



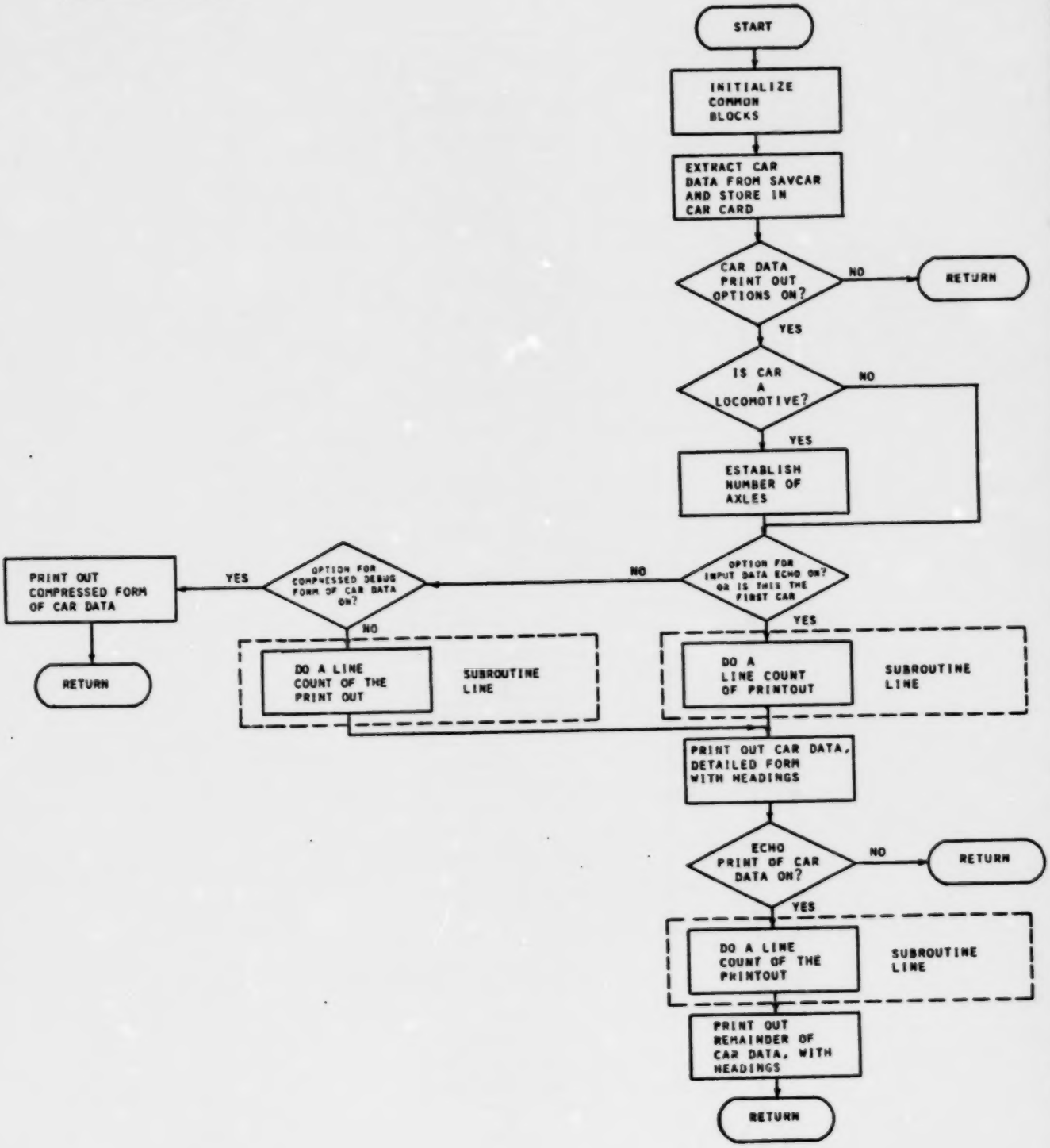
Subroutine PASS1 (page 1 of 2)



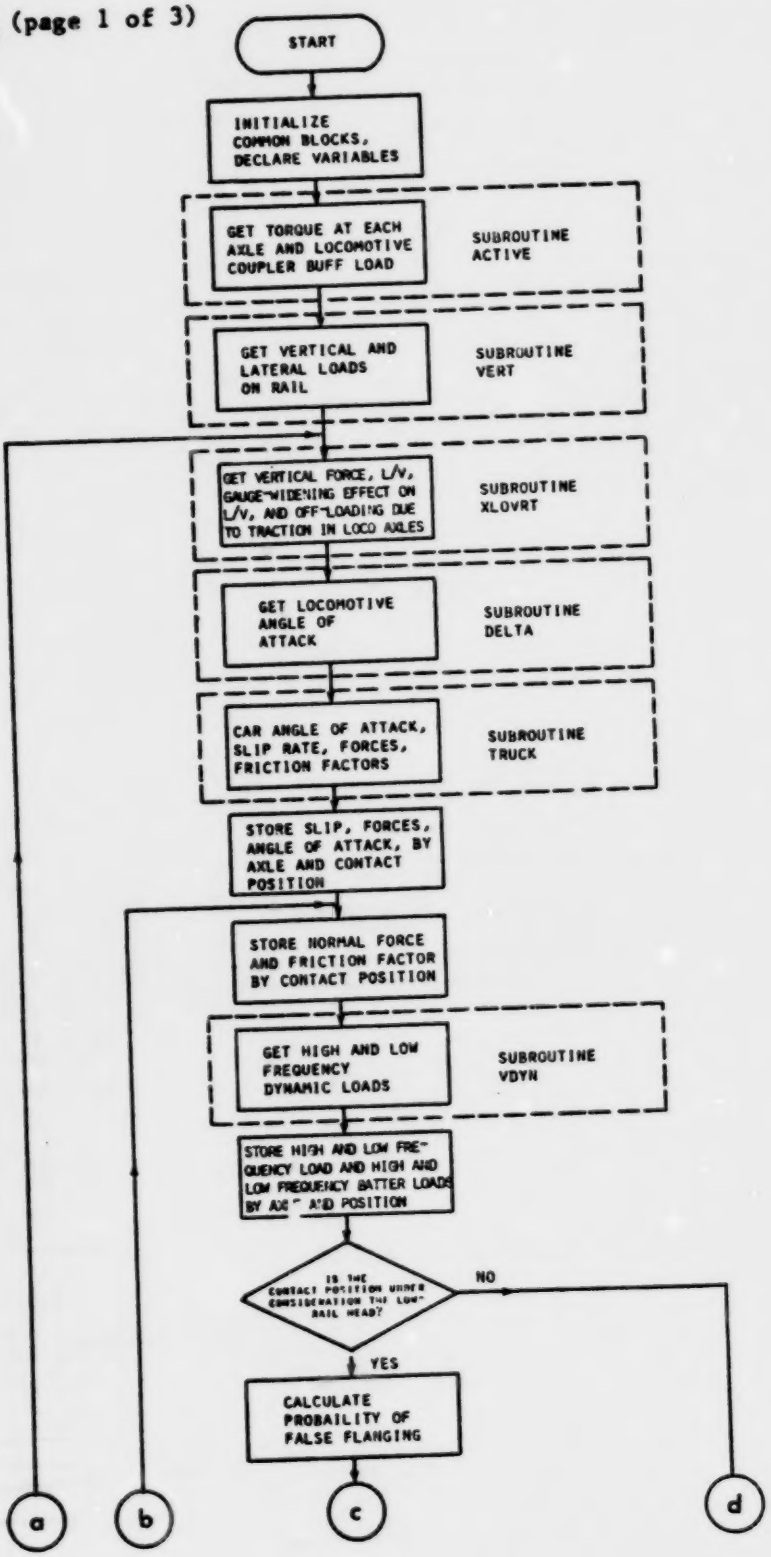
Subroutine PASS1 (page 2 of 2)



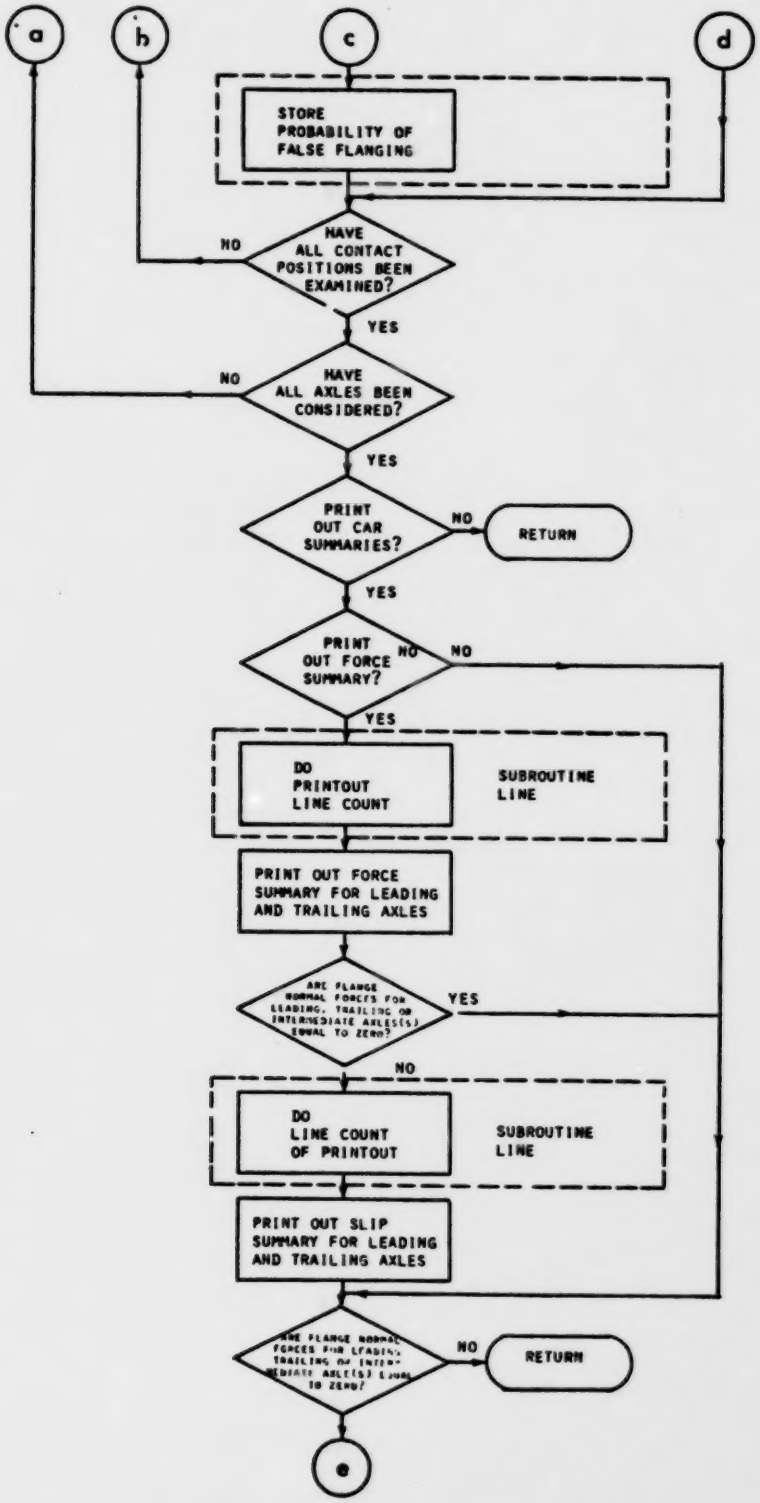
Subroutine VEHIN



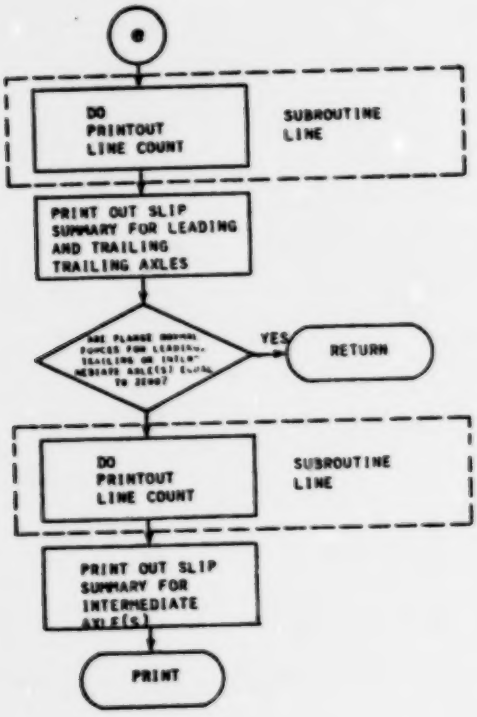
Subroutine CAR (page 1 of 3)


START
INITIALIZE COMMON BLOCKS, DECLARE VARIABLES
GET TORQUE AT EACH AXLE AND LOCOMOTIVE COUPLER BUFF LOAD
SUBROUTINE ACTIVE
GET VERTICAL AND LATERAL LOADS ON RAIL
SUBROUTINE VERT
GET VERTICAL FORCE, L/V, GAUGE-WIDENING EFFECT ON L/V, AND OFF-LOADING DUE TO TRACTION IN LOCO AXLES
SUBROUTINE XLOVRT
GET LOCOMOTIVE ANGLE OF ATTACK
SUBROUTINE DELTA
CAR ANGLE OF ATTACK, SLIP RATE, FORCES, FRICTION FACTORS
SUBROUTINE TRUCK
STORE SLIP, FORCES, ANGLE OF ATTACK, BY AXLE AND CONTACT POSITION
STORE NORMAL FORCE AND FRICTION FACTOR BY CONTACT POSITION
GET HIGH AND LOW FREQUENCY DYNAMIC LOADS
SUBROUTINE VDYN
STORE HIGH AND LOW FREQUENCY LOAD AND HIGH AND LOW FREQUENCY BATTER LOADS BY AXLE AND POSITION
IS THE CONTACT POSITION UNDER CONSIDERATION THE LOW RAIL HEAD?
NO
YES
CALCULATE PROBAILITY OF FALSE FLANGING
a
b
c
d

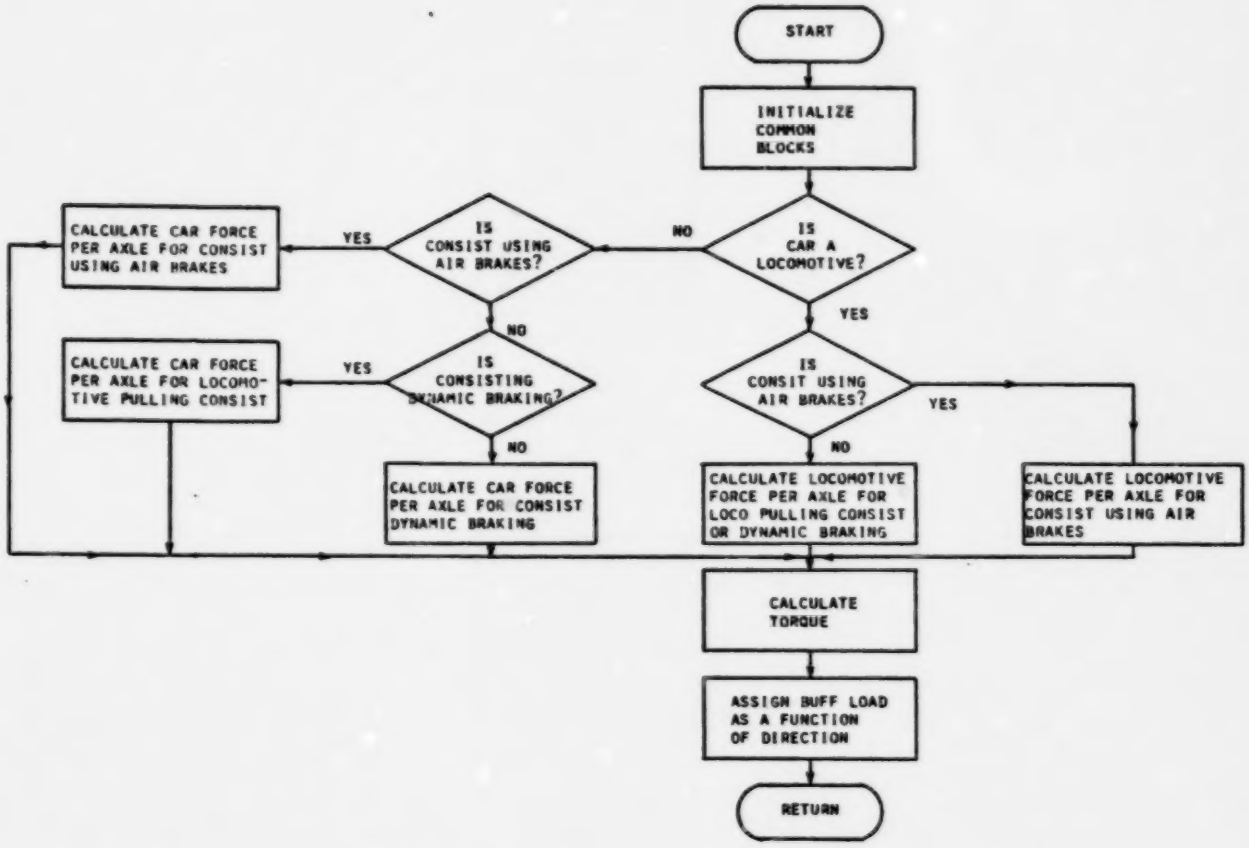
Subroutine CAR (page 2 of 3)



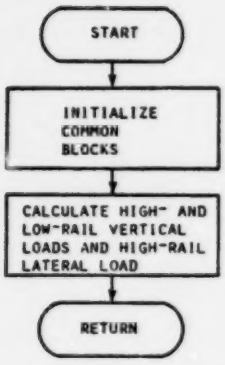
Subroutine CAR (page 3 of 3)



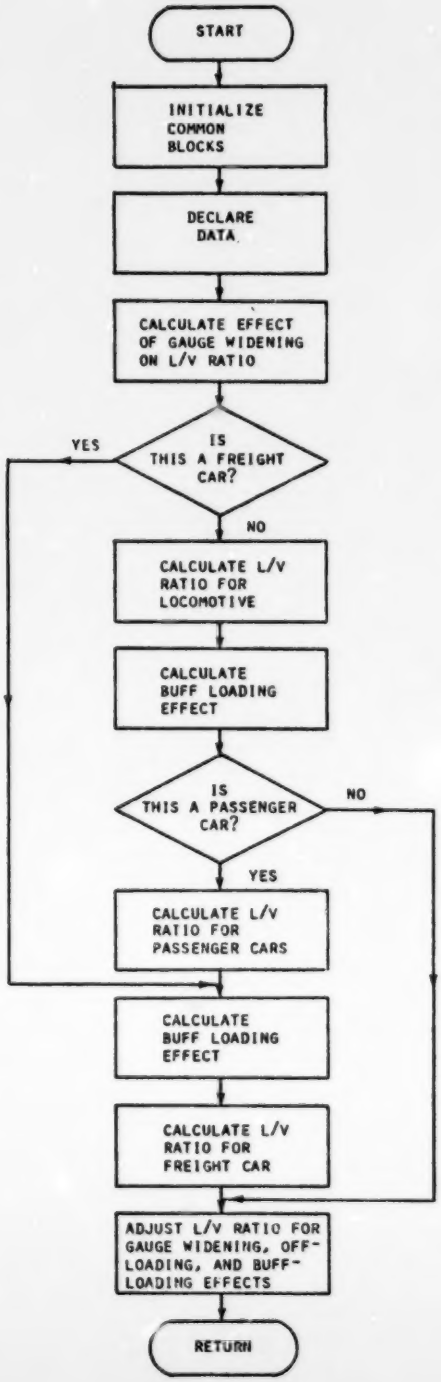
Subroutine ACTIVE


START
INITIALIZE COMMON BLOCKS
IS CAR A LOCOMOTIVE?
NO
YES
IS CONSIST USING AIR BRAKES?
YES
CALCULATE CAR FORCE PER AXLE FOR CONSIST USING AIR BRAKES
NO
IS CONSISTING DYNAMIC BRAKING?
YES
CALCULATE CAR FORCE PER AXLE FOR LOCOMOTIVE PULLING CONSIST
NO
CALCULATE CAR FORCE PER AXLE FOR CONSIST DYNAMIC BRAKING
IS CONSIT USING AIR BRAKES?
YES
NO
CALCULATE LOCOMOTIVE FORCE PER AXLE FOR CONSIST USING AIR BRAKES
CALCULATE LOCOMOTIVE FORCE PER AXLE FOR LOCO PULLING CONSIST OR DYNAMIC BRAKING
CALCULATE TORQUE
ASSIGN BUFF LOAD AS A FUNCTION OF DIRECTION
RETURN

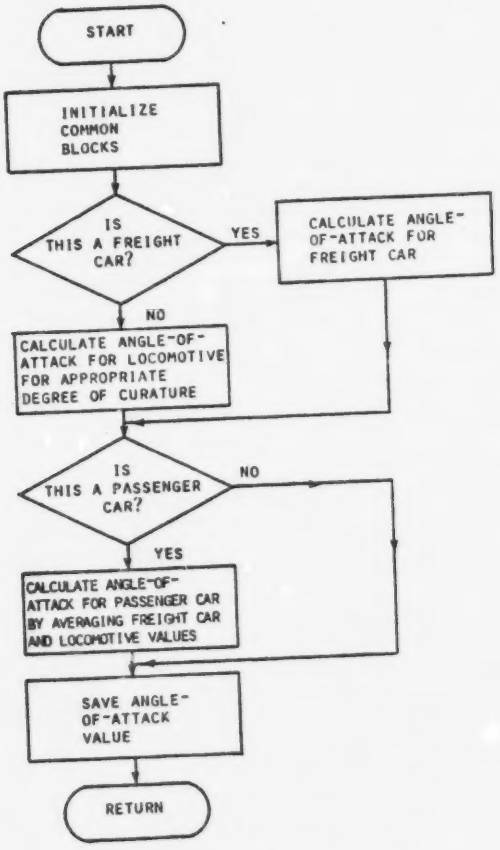
Subroutine VERT



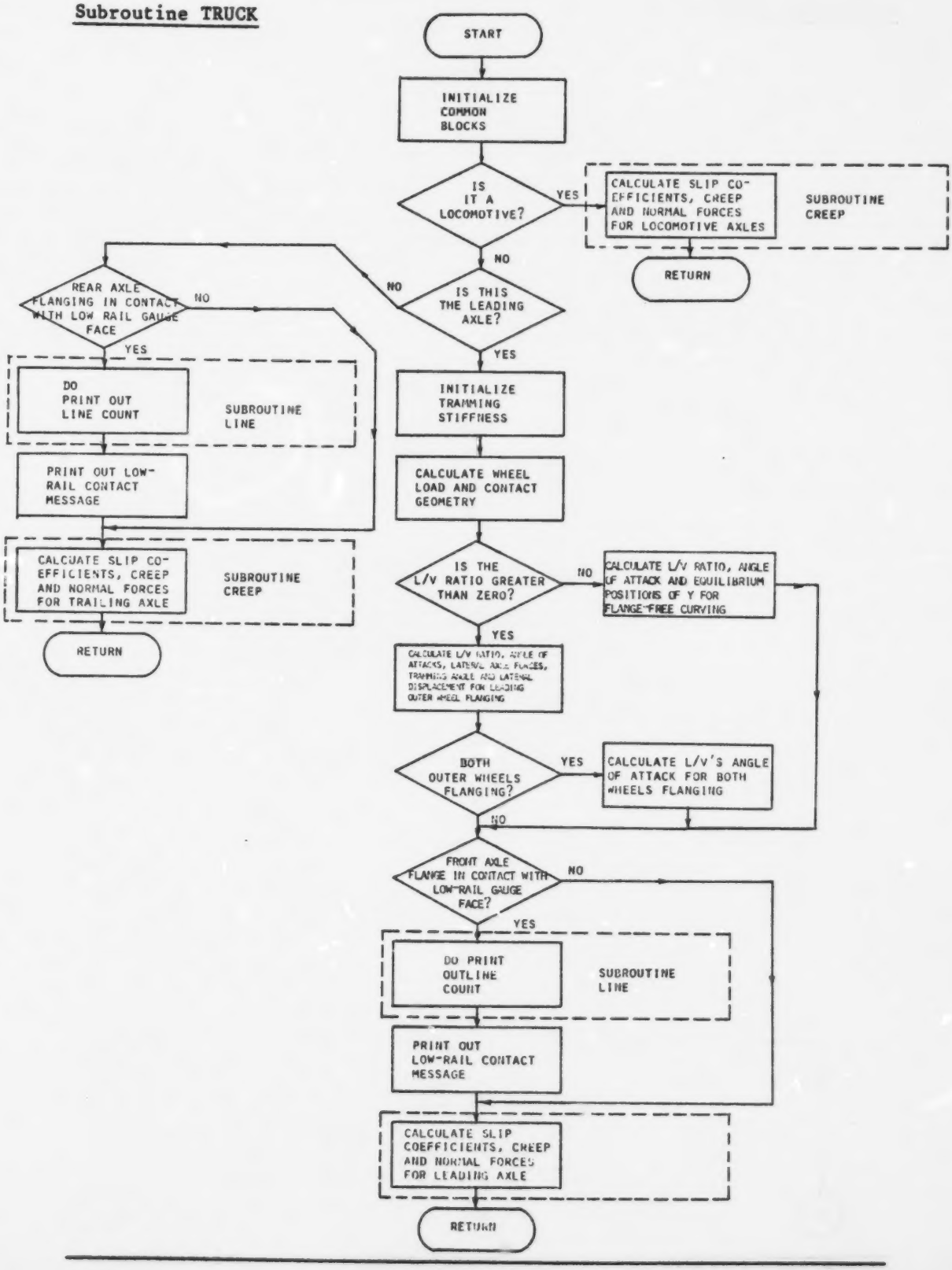
Subroutine XLOVRT



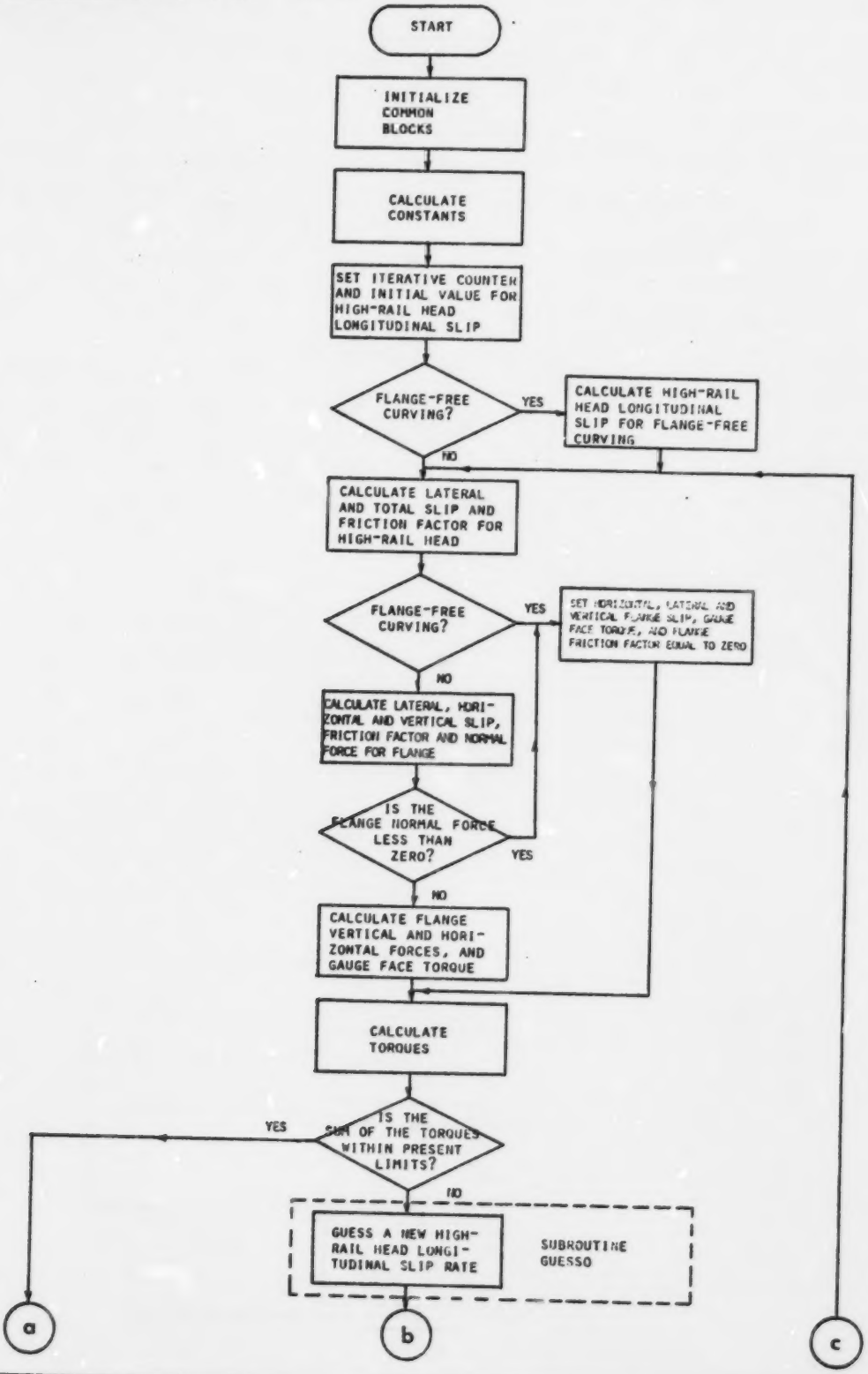
Subroutine DELTA



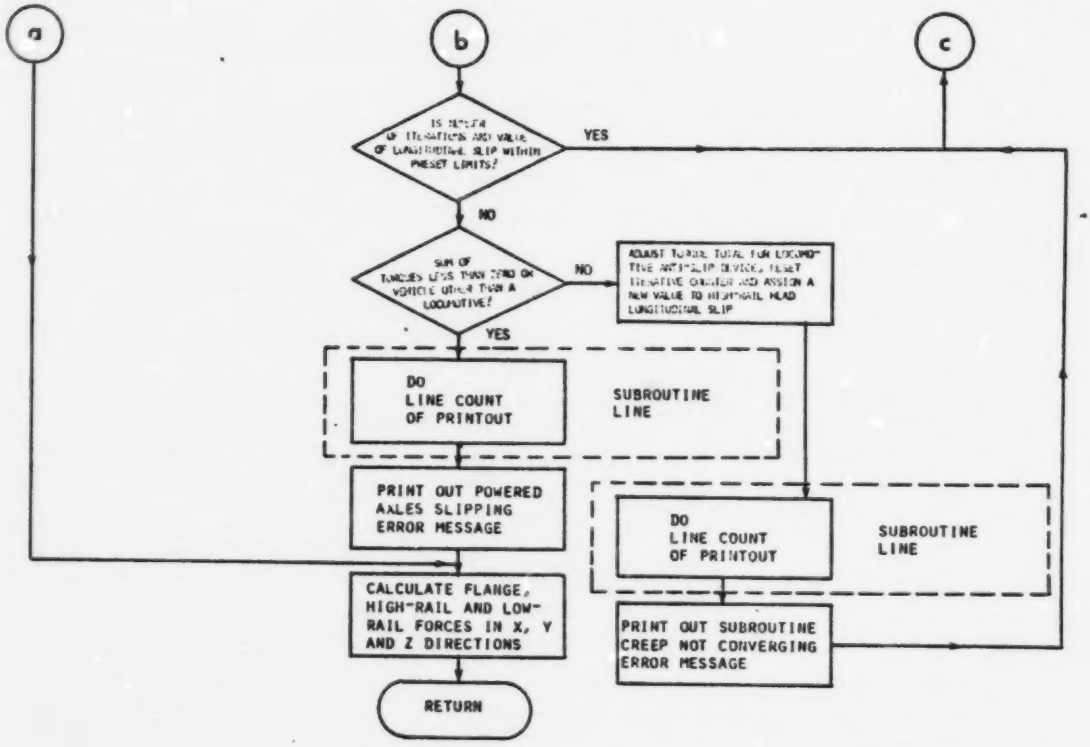
Subroutine TRUCK


START
INITIALIZE COMMON BLOCKS
IS IT A LOCOMOTIVE?
YES
CALCULATE SLIP COEFFICIENTS, CREEP AND NORMAL FORCES FOR LOCOMOTIVE AXLES
SUBROUTINE CREEP
RETURN
NO
IS THIS THE LEADING AXLE?
NO
YES
INITIALIZE TRAMMING STIFFNESS
CALCULATE WHEEL LOAD AND CONTACT GEOMETRY
IS THE L/V RATIO GREATER THAN ZERO?
NO
CALCULATE L/V RATIO, ANGLE OF ATTACK AND EQUILIBRIUM POSITIONS OF Y FOR FLANGE-FREE CURVING
YES
CALCULATE L/V RATIO, ANGLE OF ATTACKS, LATERAL AXLE FORCES, TRAMMING ANGLE AND LATERAL DISPLACEMENT FOR LEADING OUTER WHEEL FLANGING
BOTH OUTER WHEELS FLANGING?
YES
CALCULATE L/V'S ANGLE OF ATTACK FOR BOTH WHEELS FLANGING
NO
FRONT AXLE FLANGE IN CONTACT WITH LOW-RAIL GAUGE FACE?
NO
YES
DO PRINT OUTLINE COUNT
SUBROUTINE LINE
PRINT OUT LOW-RAIL CONTACT MESSAGE
CALCULATE SLIP COEFFICIENTS, CREEP AND NORMAL FORCES FOR LEADING AXLE
RETURN
REAR AXLE FLANGING IN CONTACT WITH LOW RAIL GAUGE FACE
NO
YES
DO PRINT OUT LINE COUNT
SUBROUTINE LINE
PRINT OUT LOW-RAIL CONTACT MESSAGE
CALCUATE SLIP COEFFICIENTS, CREEP AND NORMAL FORCES FOR TRAILING AXLE
SUBROUTINE CREEP
RETURN

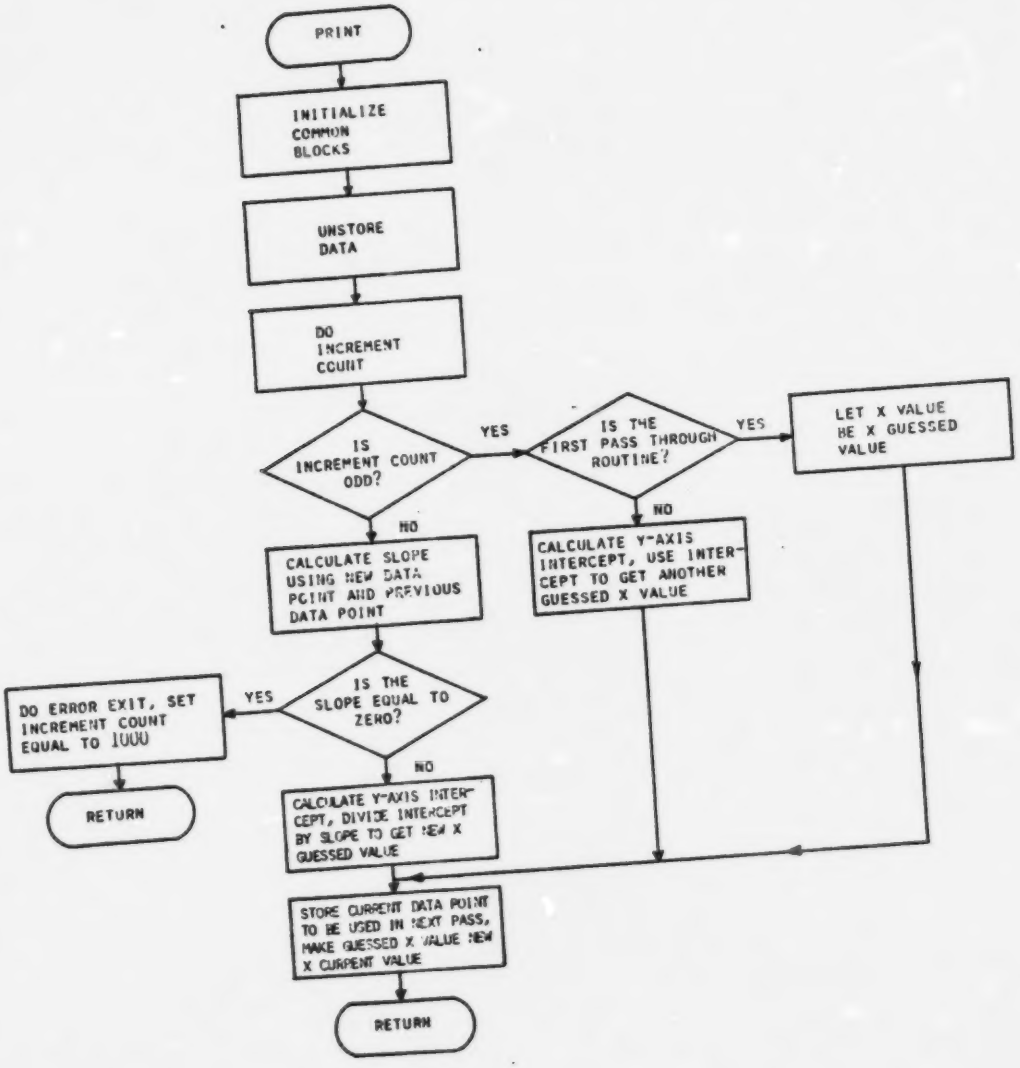
Subroutine CREEP (page 1 of 2)


START
INITIALIZE COMMON BLOCKS
CALCULATE CONSTANTS
SET ITERATIVE COUNTER AND INITIAL VALUE FOR HIGH-RAIL HEAD LONGITUDINAL SLIP
FLANGE-FREE CURVING?
YES
CALCULATE HIGH-RAIL HEAD LONGITUDINAL SLIP FOR FLANGE-FREE CURVING
NO
CALCULATE LATERAL AND TOTAL SLIP AND FRICTION FACTOR FOR HIGH-RAIL HEAD
FLANGE-FREE CURVING?
YES
SET HORIZONTAL, LATERAL AND VERTICAL FLANGE SLIP, GAUGE FACE TORQUE, AND FLANGE FRICTION FACTOR EQUAL TO ZERO
NO
CALCULATE LATERAL, HORIZONTAL AND VERTICAL SLIP, FRICTION FACTOR AND NORMAL FORCE FOR FLANGE
IS THE FLANGE NORMAL FORCE LESS THAN ZERO?
YES
NO
CALCULATE FLANGE VERTICAL AND HORIZONTAL FORCES, AND GAUGE FACE TORQUE
CALCULATE TORQUES
IS THE SUM OF THE TORQUES WITHIN PRESENT LIMITS?
YES
NO
GUESS A NEW HIGH-RAIL HEAD LONGITUDINAL SLIP RATE
SUBROUTINE GUESSO
a
b
c

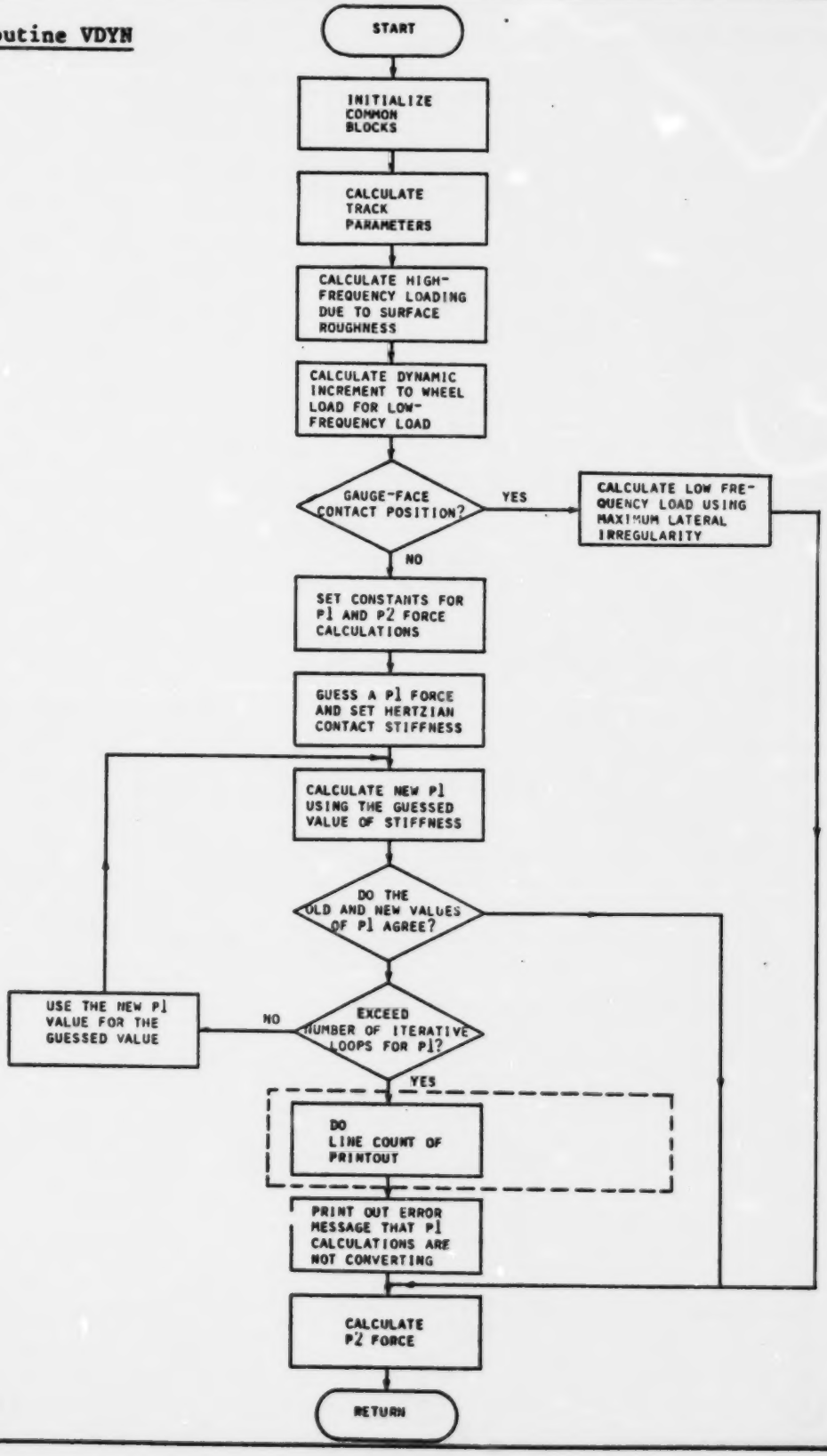
Subroutine CREEP (page 2 of 2)



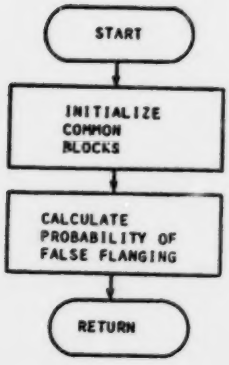
Subroutine GUESSO


PRINT
INITIALIZE COMMON BLOCKS
UNSTORE DATA
DO INCREMENT COUNT
IS INCREMENT COUNT ODD?
YES
IS THE FIRST PASS THROUGH ROUTINE?
YES
LET X VALUE BE X GUESSED VALUE
NO
CALCULATE SLOPE USING NEW DATA POINT AND PREVIOUS DATA POINT
CALCULATE Y-AXIS INTERCEPT, USE INTERCEPT TO GET ANOTHER GUESSED X VALUE
IS THE SLOPE EQUAL TO ZERO?
YES
DO ERROR EXIT, SET INCREMENT COUNT EQUAL TO 1000
RETURN
NO
CALCULATE Y-AXIS INTERCEPT, DIVIDE INTERCEPT BY SLOPE TO GET NEW X GUESSED VALUE
STORE CURRENT DATA POINT TO BE USED IN NEXT PASS, MAKE GUESSED X VALUE NEW X CURRENT VALUE
RETURN

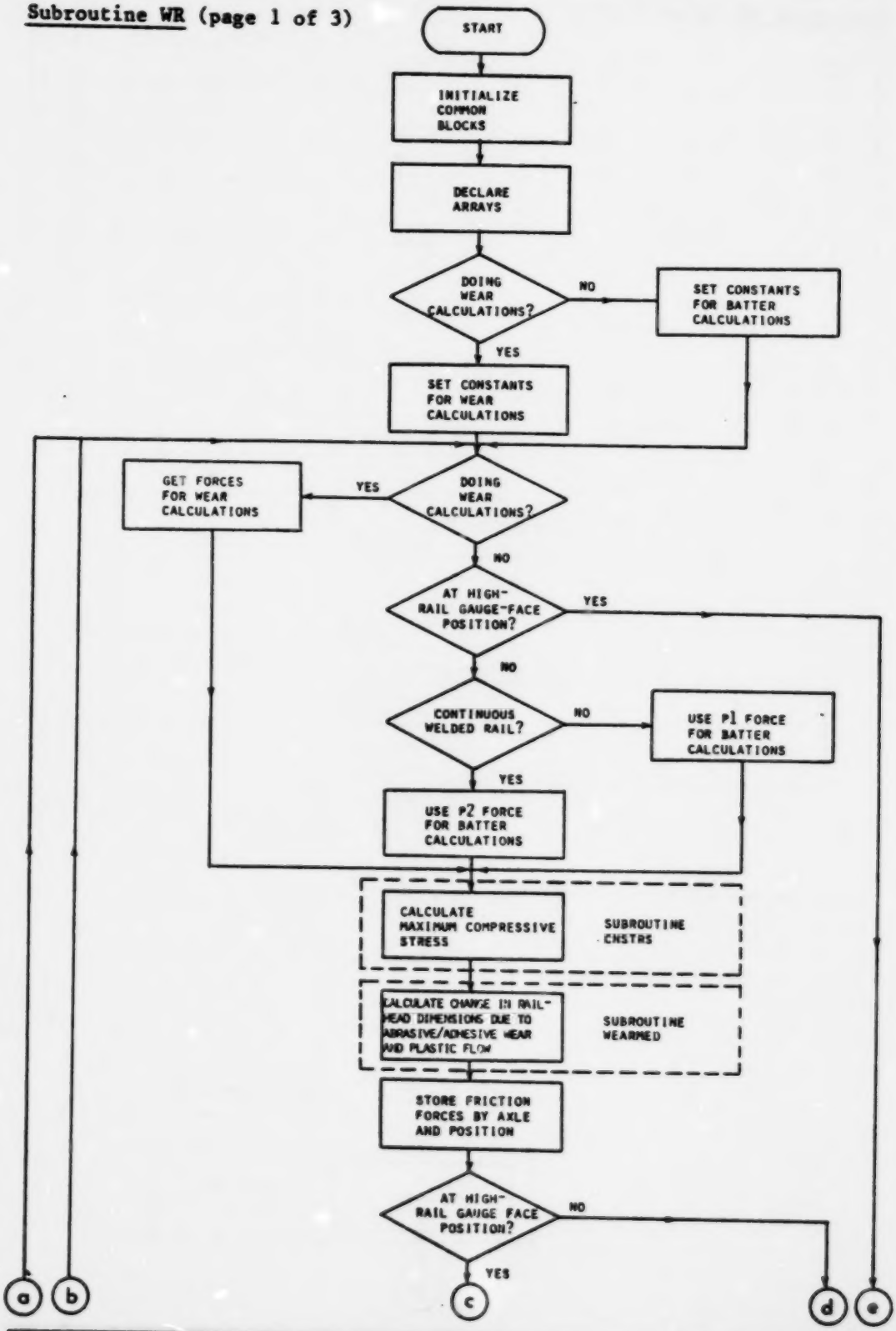
Subroutine VDYN


START
INITIALIZE COMMON BLOCKS
CALCULATE TRACK PARAMETERS
CALCULATE HIGH-FREQUENCY LOADING DUE TO SURFACE ROUGHNESS
CALCULATE DYNAMIC INCREMENT TO WHEEL LOAD FOR LOW-FREQUENCY LOAD
GAUGE-FACE CONTACT POSITION?
YES
CALCULATE LOW FREQUENCY LOAD USING MAXIMUM LATERAL IRREGULARITY
NO
SET CONSTANTS FOR P1 AND P2 FORCE CALCULATIONS
GUESS A P1 FORCE AND SET HERTZIAN CONTACT STIFFNESS
CALCULATE NEW P1 USING THE GUESSED VALUE OF STIFFNESS
DO THE OLD AND NEW VALUES OF P1 AGREE?
USE THE NEW P1 VALUE FOR THE GUESSED VALUE
NO
EXCEED NUMBER OF ITERATIVE LOOPS FOR P1?
YES
DO
LINE COUNT OF PRINTOUT
PRINT OUT ERROR MESSAGE THAT P1 CALCULATIONS ARE NOT CONVERTING
CALCULATE P2 FORCE
RETURN

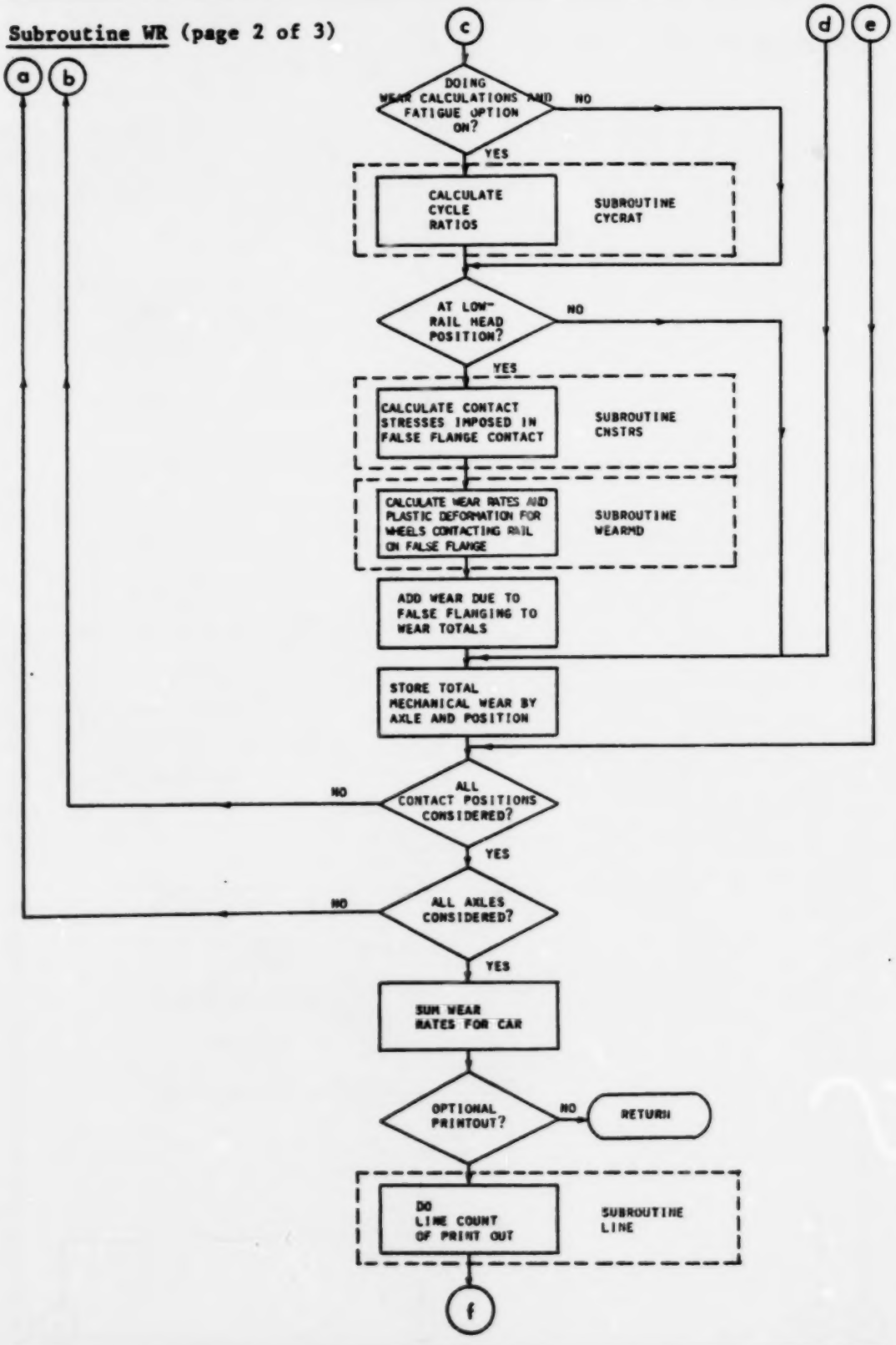
Subroutine REVCON



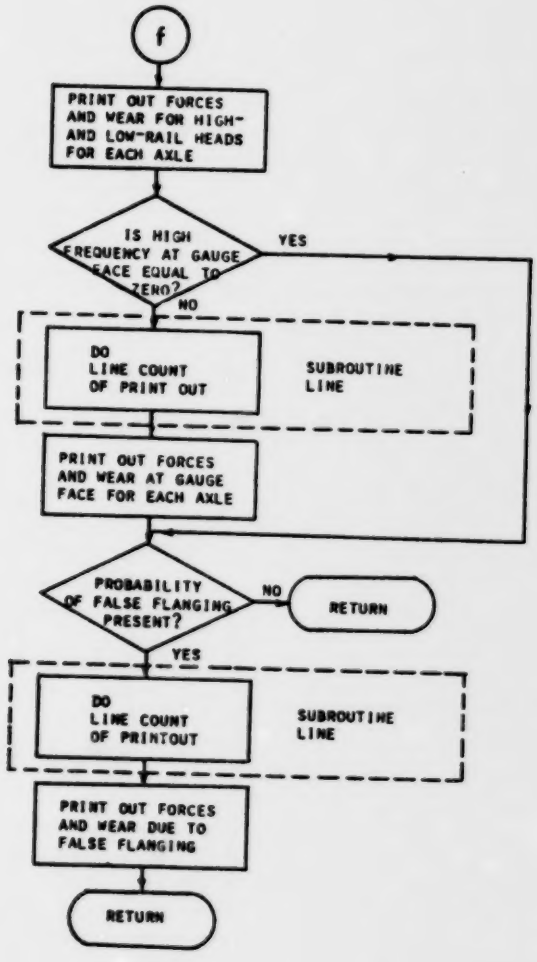
Subroutine WR (page 1 of 3)



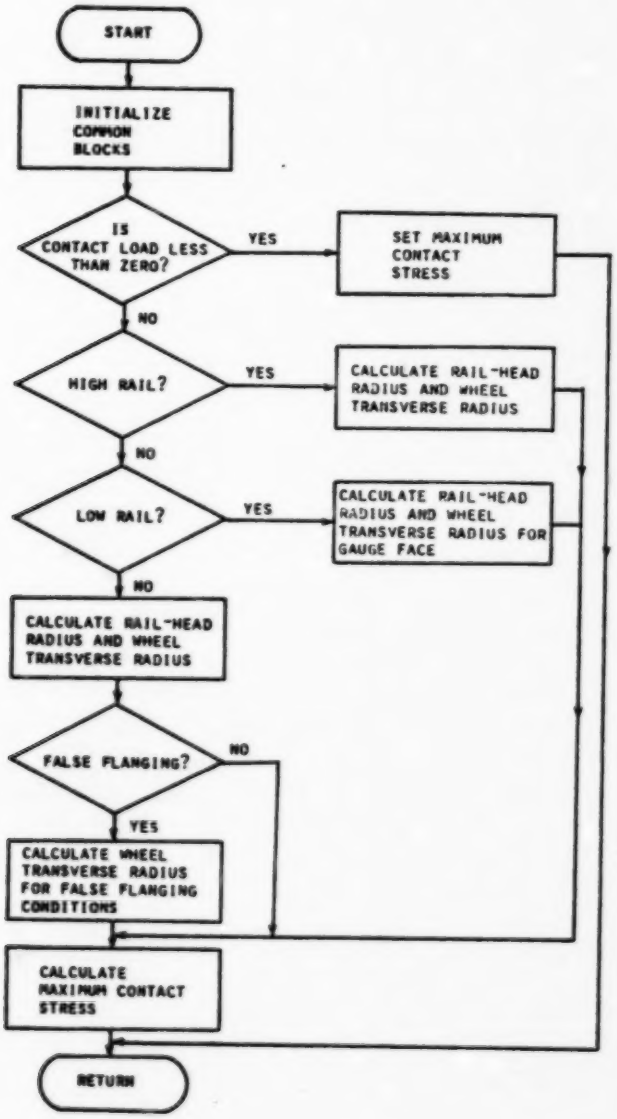
Subroutine WR (page 2 of 3)



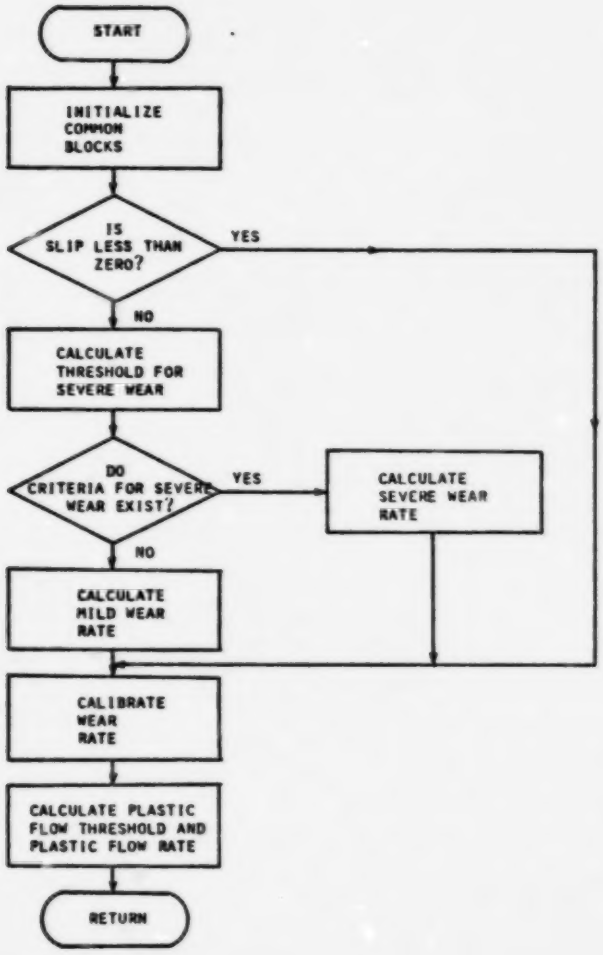
Subroutine WR (page 3 of 3)


f
PRINT OUT FORCES AND WEAR FOR HIGH- AND LOW-RAIL HEADS FOR EACH AXLE
IS HIGH FREQUENCY AT GAUGE FACE EQUAL TO ZERO?
YES
NO
DO LINE COUNT OF PRINT OUT
SUBROUTINE LINE
PRINT OUT FORCES AND WEAR AT GAUGE FACE FOR EACH AXLE
PROBABILITY OF FALSE FLANGING PRESENT?
NO
RETURN
YES
DO LINE COUNT OF PRINTOUT
SUBROUTINE LINE
PRINT OUT FORCES AND WEAR DUE TO FALSE FLANGING
RETURN

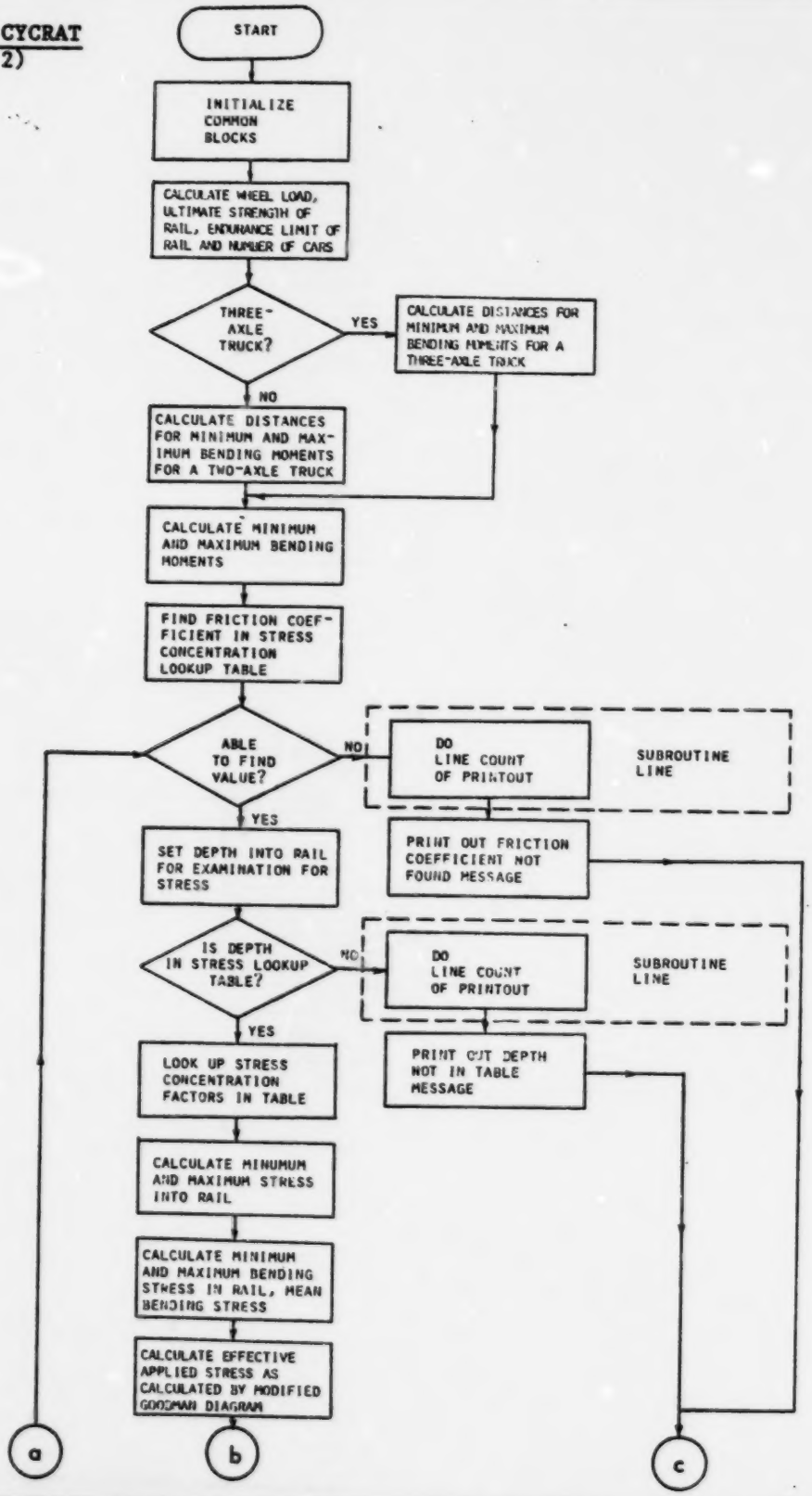
Subroutine CNSTRS



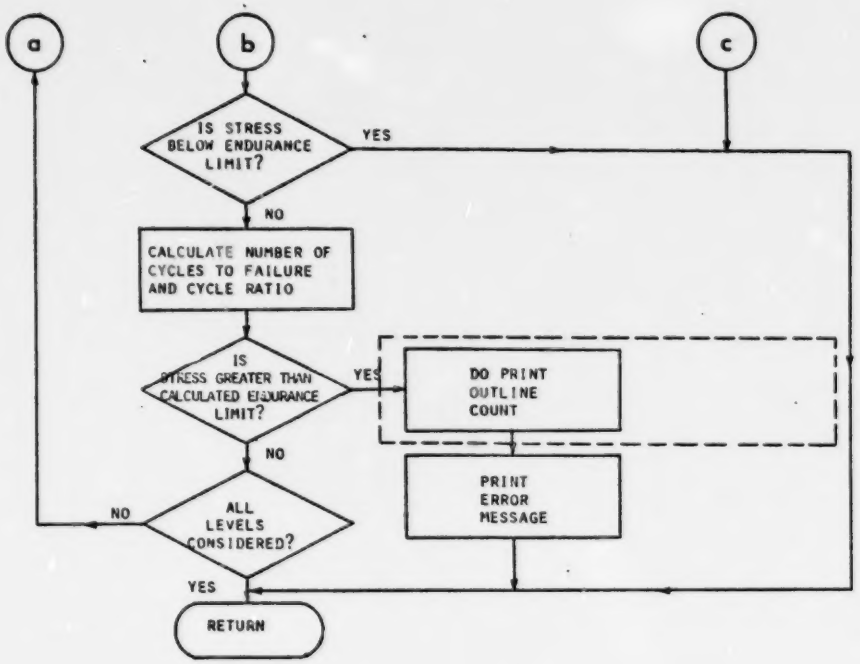
Subroutine WEARMD



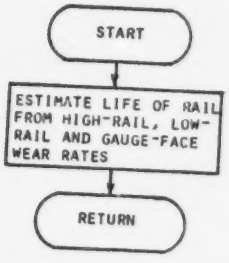
Subroutine CYCRAT
(page 1 of 2)


START
INITIALIZE COMMON BLOCKS
CALCULATE WHEEL LOAD, ULTIMATE STRENGTH OF RAIL, ENDURANCE LIMIT OF RAIL AND NUMBER OF CARS
THREE-AXLE TRUCK?
YES
CALCULATE DISTANCES FOR MINIMUM AND MAXIMUM BENDING MOMENTS FOR A THREE-AXLE TRUCK
NO
CALCULATE DISTANCES FOR MINIMUM AND MAXIMUM BENDING MOMENTS FOR A TWO-AXLE TRUCK
CALCULATE MINIMUM AND MAXIMUM BENDING MOMENTS
FIND FRICTION COEFFICIENT IN STRESS CONCENTRATION LOOKUP TABLE
ABLE TO FIND VALUE?
NO
DO LINE COUNT OF PRINTOUT
SUBROUTINE LINE
PRINT OUT FRICTION COEFFICIENT NOT FOUND MESSAGE
YES
SET DEPTH INTO RAIL FOR EXAMINATION FOR STRESS
IS DEPTH IN STRESS LOOKUP TABLE?
NO
DO LINE COUNT OF PRINTOUT
SUBROUTINE LINE
PRINT OUT DEPTH NOT IN TABLE MESSAGE
YES
LOOK UP STRESS CONCENTRATION FACTORS IN TABLE
CALCULATE MINUMUM AND MAXIMUM STRESS INTO RAIL
CALCULATE MINIMUM AND MAXIMUM BENDING STRESS IN RAIL, MEAN BENDING STRESS
CALCULATE EFFECTIVE APPLIED STRESS AS CALCULATED BY MODIFIED GOODMAN DIAGRAM
a
b
c

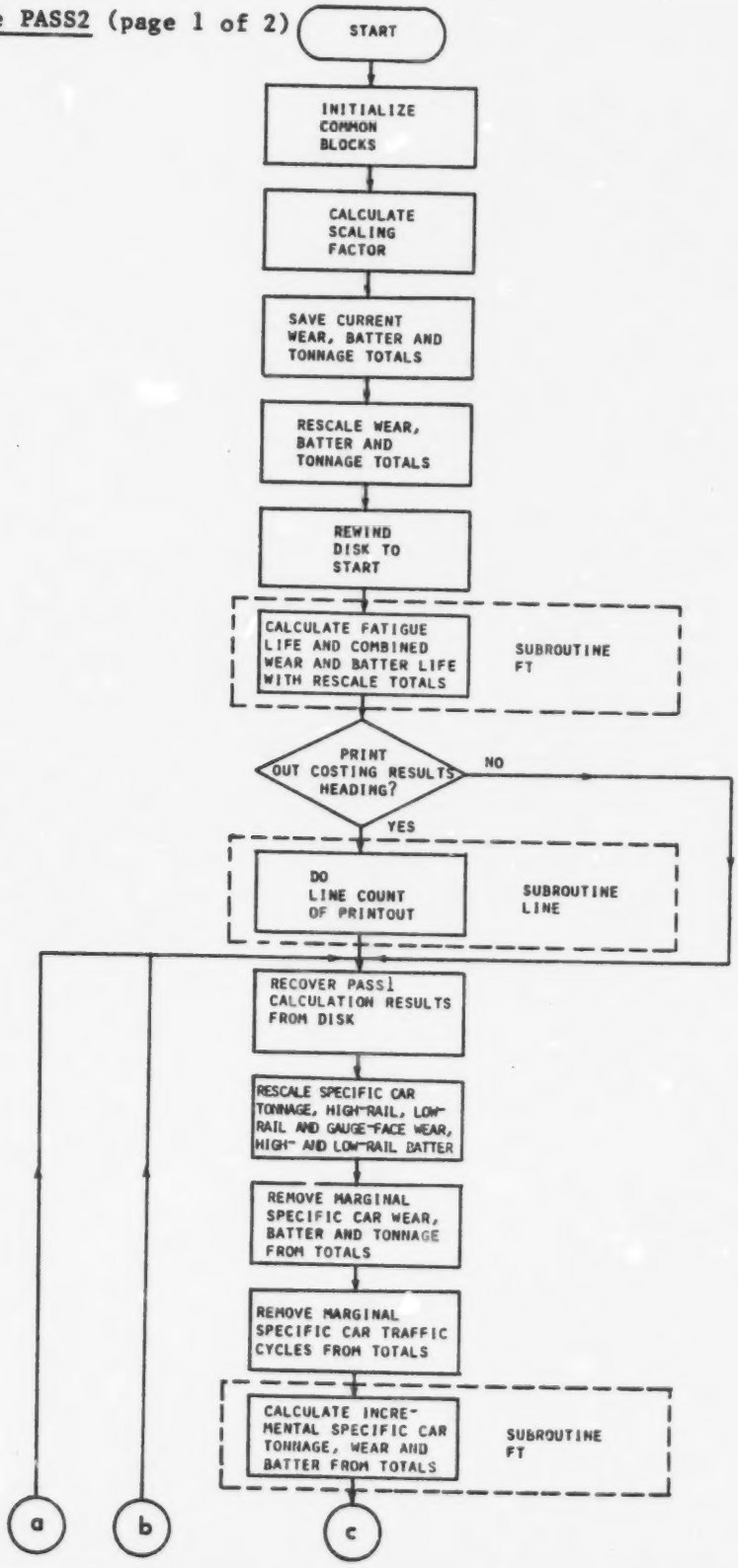
Subroutine CYCRAT (page 2 of 2)



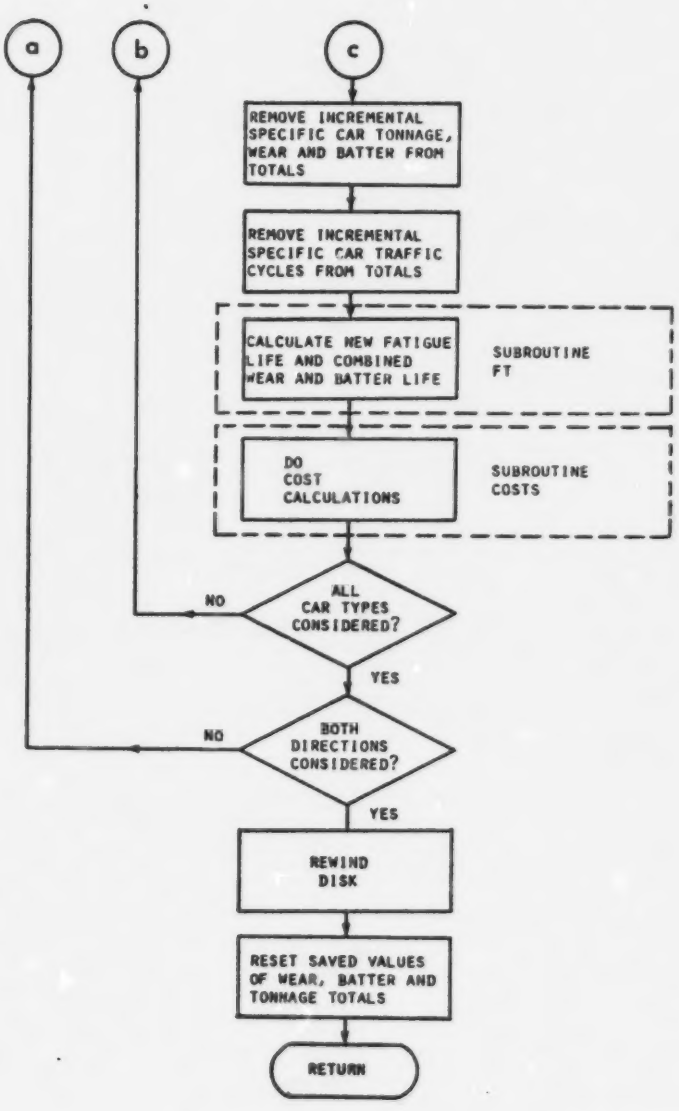
Subroutine LIFE



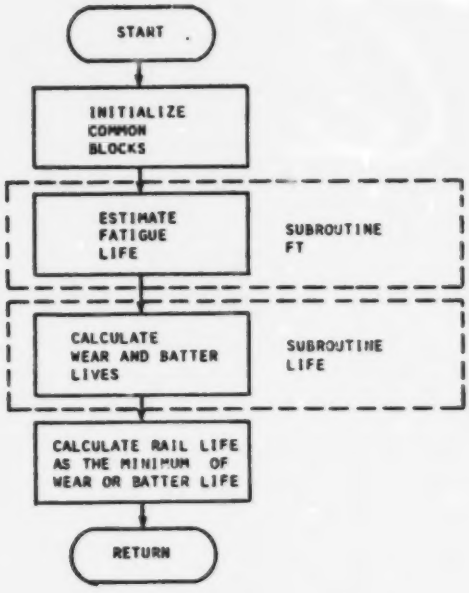
Subroutine PASS2 (page 1 of 2)


START
INITIALIZE COMMON BLOCKS
CALCULATE SCALING FACTOR
SAVE CURRENT WEAR, BATTER AND TONNAGE TOTALS
RESCALE WEAR, BATTER AND TONNAGE TOTALS
REWIND DISK TO START
CALCULATE FATIGUE LIFE AND COMBINED WEAR AND BATTER LIFE WITH RESCALE TOTALS
SUBROUTINE FT
PRINT OUT COSTING RESULTS HEADING?
NO
YES
DO LINE COUNT OF PRINTOUT
SUBROUTINE LINE
RECOVER PASS1 CALCULATION RESULTS FROM DISK
RESCALE SPECIFIC CAR TONNAGE, HIGH-RAIL, LOW-RAIL AND GAUGE-FACE WEAR, HIGH- AND LOW-RAIL BATTER
REMOVE MARGINAL SPECIFIC CAR WEAR, BATTER AND TONNAGE FROM TOTALS
REMOVE MARGINAL SPECIFIC CAR TRAFFIC CYCLES FROM TOTALS
CALCULATE INCREMENTAL SPECIFIC CAR TONNAGE, WEAR AND BATTER FROM TOTALS
SUBROUTINE FT
a
b
c

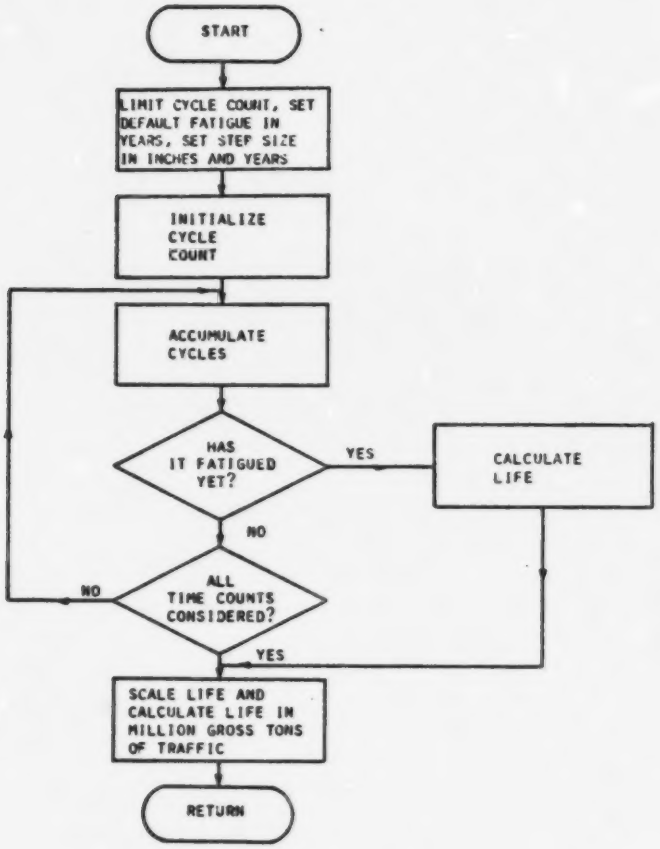
Subroutine PASS2 (page 2 of 2)



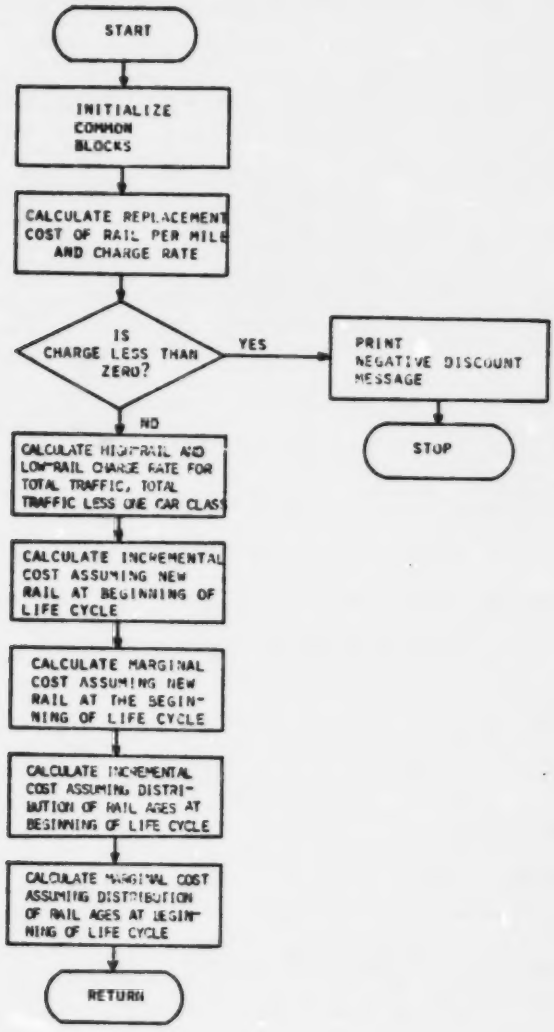
Subroutine FT



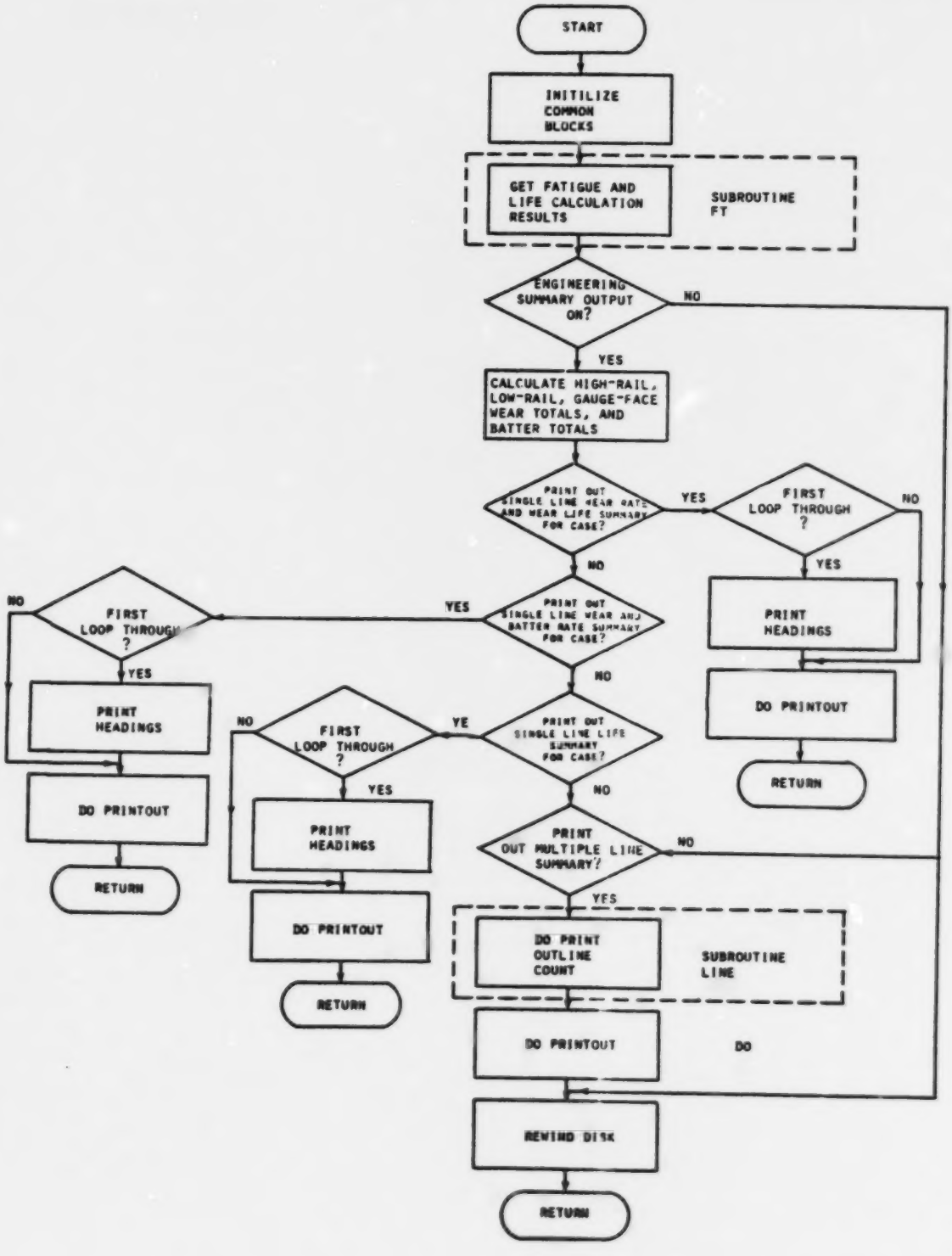
Subroutine FATLIF



Subroutine COSTS


START
INITIALIZE COMMON BLOCKS
CALCULATE REPLACEMENT COST OF RAIL PER MILE AND CHARGE RATE
IS CHARGE LESS THAN ZERO?
YES
PRINT NEGATIVE DISCOUNT MESSAGE
STOP
NO
CALCULATE HIGH-RAIL AND LOW-RAIL CHARGE RATE FOR TOTAL TRAFFIC, TOTAL TRAFFIC LESS ONE CAR CLASS
CALCULATE INCREMENTAL COST ASSUMING NEW RAIL AT BEGINNING OF LIFE CYCLE
CALCULATE MARGINAL COST ASSUMING NEW RAIL AT THE BEGINNING OF LIFE CYCLE
CALCULATE INCREMENTAL COST ASSUMING DISTRIBUTION OF RAIL AGES AT BEGINNING OF LIFE CYCLE
CALCULATE MARGINAL COST ASSUMING DISTRIBUTION OF RAIL AGES AT BEGINNING OF LIFE CYCLE
RETURN

Subroutine PRNT



APPENDIX D

SAMPLE INPUT DATA FILE

```
1011101 80 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
20., 4., 4.
0., -1., 0.
1.2, 0.0
2, 88.2, 15000.0, 1.0, 0.75, 0.010, 0.60, 44., 153.75, 0.25, 0
.625
0.15, 0.06, 127., 33.
2, 2, 18475., 1600., 32., 78.70, 80., 90. SEVENTY TON
2, 2,  5000., 1600., 32., 21.30, 80., 55. EMPTY CARS
2, 2, 33750., 2000., 36.,.01000, 80., 90. HUNDRED TON
2, 2,  6250., 2000., 36.,.00185, 80., 55. EMPTY CARS
2, 2, 33750., 2000., 36., 1.000, 80., 90. HUNDRED TON
2, 2,  6250., 2000., 36.,.18500, 80., 90. EMPTY CARS
2, 2, 18475., 1600., 32., 1.000, 80., 90. SEVENTY TON
2, 2,  5000., 1600., 32.,.18500, 80., 55. EMPTY CARS
V=60
RUN 60 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
V=40.
RUN 40 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
V=30.
RUN 30 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
V=20
RUN 20 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
V=10
RUN 10 MPH, 0 CRV, CONCRETE TIES, 260 BHN, 132 LB JNT RAIL, GOOD MAINT
```

APPENDIX E

SAMPLE CALIBRATION FILE

```
ROAD MAINTENANCE COST MODEL CALIBRATION FILE: VERSION 16.01
MATERIAL PROPERTIES: E=3.0E7, G=1.15E7, POISON=.3
BRINELL HARDNESS: HIGH=330, LOW=260
TRACK: L=5.0E7, C=8.3E7
UNLUBRICATED FRICTION: HI=.35, LO=.35, GF=.35, MUEMAX=.6
LUBRICATED FRICTION:   HI=.30, LO=.30, GF=.10, MUEMAX=.6
RAIL CURVATURES:  HI=11.5, LO=11.5, GF=1.3, ADJ HI: K=7.5, SUBT=0.0
WHEEL CURVATURES: HI=-22., LO=-22., FLANGE=-1.6, LO FOR FF=20.
GEOMETRY FOR CREEP: A=.32, FANGLE=62.5, TDOP DELTAS=.0, .0
MARGINALS BASED ON: .01 MMGT
CAL FOR LOADER: DELTA CURVE=0.4,WORK HRD HI=1.16,5 LO=1.16,5 GF=1.0,99.
CAL FOR LOCO:   HP=2.5, LPC=4, SPD=7., EMPO=6250., DYN BRAKING=.0
CAL FOR ACTIVE: RUNIN/RUNOUT ACCEL=0.000
CAL FOR XLOVRT: OFF BAL SPD=0.3, GAGE WIDENING=0., BUFF=.0,.0
CAL FOR TRUCK:  TRAM=2655.,.3164
CAL FOR REVCON: STD DEV/AXLE=0.43,1.13,1.13, CRIT FORCE=99.0
CAL FOR CYCRAT: SE=135,SU=500,MAX CYCLES=5.E7,ONE=1.0,CYCLES=1.0
CAL FOR WR: (WEAR) ABR=1.66, PLASTIC=2.5, (BATTER) CWR=1.0, JOINTED=.333
CAL FOR WEARMD: ABRASION HI=1.0, LO=1.0, GF=0.75
                PLASTIC FLOW HI=1.0, LO=1.0, GF=0.75
                SEVER WEAR=1.0, PLASTIC FLOW THRESHOLD=1.0
CAL FOR FATLIF: LIFE=100, MINER=1.0, OFFSET=50.
```

APPENDIX F.1

```
ROAD MAINTENANCE COST MODEL CALIBRATION FILE: VERSION 16.08                16.080
MATERIAL PROPERTIES: E=3.0E7, G=1.15E7, POISON=.3                      0.30E+08 0.12E+08    0.300
BRINELL HARDNESS: HIGH=320, LOW=240                                      320.000  240.000
                                                                       0.50E+08 0.83E+08
TRACK: L=2.0E7, C=8.3E7
UNLUBRICATED FRICTION: HI=.35, LO=.35, BF=.35, MUEMAX=.6                   0.350    0.350    0.350    0.600
LUBRICATED FRICTION:   HI=.30, LO=.30, BF=.10, MUEMAX=.6                   0.300    0.300    0.100    0.600
RAIL CURVATURES:  HI=11.5, LO=11.5, BF 1.3, ADJ HI: K=7.5, SUBT=0.0       11.500   11.500    1.300    7.500    0.000
WHEEL CURVATURES: HI=-22., LO=-22., FLANGE=-1.4, LO FOR FF=20.            -22.000  -22.000   -1.400   20.000
GEOMETRY FOR CREEP: A=.32, FANGLE=42.5, TDOP DELTAB=.0, .0                 0.320   42.500    0.000    0.000
                                                                           0.010
MARGINALS BASED ON: .01 MMGT
CAL FOR LOADER: DELTA CURVE=0.4,WORK HRD HI=1.14,5 LO=1.14,5 BF=1.0,99.    0.400    1.140    5.000    1.140    5.000
                                                                           1.000   99.000
CAL FOR LOCO:   HP=2.5, LPC=4, SPD=7., EMPO=4250., DYN BRAKING=1.0         2.500    4.000    7.000 4250.000    1.000
CAL FOR ACTIVE: RUNIN/RUNOUT ACCEL=0.0005                                  0.001
CAL FOR XLOVRT: OFF BAL SPD=0.3, BASE WIDENING=.15, BUFF=.33,-.0001        0.300    0.150    0.330   -0.000
CAL FOR TRUCK:  TRAN=2655.,.5164                                        2655.000    0.516
CAL FOR REVCON: STD DEV/AXLE=0.43,1.13,1.13; CRIT FORCE=13.0               0.430    1.130    1.130   13.000
CAL FOR CYCRAT: BE=135,BU=500,MAX CYCLES=5.E7,ONE=1.0,CYCLES=1.0         135.000  500.000 0.5E+08    1.000    1.000
CAL FOR WR: (WEAR) ABR=1.44, PLASTIC=2.5, (BATTER) CWR=1.0, JOINTED=.333   1.440    2.500    1.000    0.333
CAL FOR WEARMD: ABRASION HI=1.0, LO=1.0, BF=0.75                           1.000    1.000    0.750
                PLASTIC FLOW HI=1.0, LO=1.0, BF=0.75                       1.000    1.000    0.750
                SEVER WEAR=1.0, PLASTIC FLOW THRESHOLD=1.0                 1.000    1.000
CAL FOR FATLIF: LIFE=100, MINER=1.0, OFFSET=50.                          100.000    1.000   50.000
```

APPENDIX F.2

RMCM RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN # 08-APR-82

CANADIAN INSTITUTE OF GUIDED GROUND TRANSPORT
ROAD MAINTENANCE COST MODEL VERSION 16.08

***** TRACK PARAMETER SUMMARY *****

RAIL TYPE: CWR	260. BHN	LUBRICATED
TRACK MODULUS =	2500.0	LBS/IN/IN
RAIL MASS =	132.00	LBS/YRD
TIE MASS =	61.65	LBS/FT
RAIL INERTIA =	88.20	IN**4
MAX VERT IRREG =	0.38	IN
MAX HORIZ IRREG =	0.08	IN
GAUGE WIDENING =	0.25	IN
JOINT DIP ANGLE =	0.001000	RAD
SUPPORT FACTOR =	1.000000	RATIO
TRACK CURVATURE =	6.00	DEG
SUPER ELEVATION =	3.77	IN
TRACK GRADE =	-0.58	PERCENT

***** MISCELLANEOUS PARAMETERS *****

TOTAL TRAFFIC =	16.05	MMGT
CAR TYPES FORWARD =	2	
CAR TYPES BACKHAUL =	2	
TRANSPOSAL WEAR ALLOWANCE =	0.750	IN

RMCM RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN # 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE FORWARD DIRECTION GRADE= -0.34 %

TRAFFIC =	8.70	MMGT	SPEED =	30.0 MPH
WHEEL LOADING =	31000.0	LB	UNSPRUNG MASS =	5484.0 LB
WHEEL RADIUS =	20.00	IN	CENTER OF GRAVITY =	90.00 IN

RMCM RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN # 08-APR-82
VEHICLE NUMBER 2: 168000. LB FREIGHT CAR FORWARD DIRECTION GRADE= -0.34 %

TRAFFIC =	10.00	MMGT	SPEED =	30.0 MPH
WHEEL LOADING =	23500.0	LB	UNSPRUNG MASS =	1995.0 LB
WHEEL RADIUS =	18.00	IN	CENTER OF GRAVITY =	90.00 IN

RMCM RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN # 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE BACKHAUL DIRECTION GRADE= 0.34 %

TRAFFIC =	0.35	MMGT	SPEED =	30.0 MPH
WHEEL LOADING =	31000.0	LB	UNSPRUNG MASS =	5484.0 LB
WHEEL RADIUS =	20.00	IN	CENTER OF GRAVITY =	90.00 IN

RMCM RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN # 08-APR-82
VEHICLE NUMBER 2: 140000. LB FREIGHT CAR BACKHAUL DIRECTION GRADE= 0.34 %

TRAFFIC =	5.00	MMGT	SPEED =	30.0 MPH
WHEEL LOADING =	17500.0	LB	UNSPRUNG MASS =	1995.0 LB
WHEEL RADIUS =	18.00	IN	CENTER OF GRAVITY =	90.00 IN

APPENDIX F.3

```
RHCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL    RUN #              08-APR-82
OUTP=20000000 LASTP=1 PRTOUT=2 TOTMGT= 16.05 NCARS= 2, 2
DCURV= 6.0 SE=3.77 GRAD=-0.34 D= 6.4
RI= 28.2 U= 2500. TRV=0.38 TRL=0.08 DIP=0.0010 RO=1.0 MR=44.00 MT= 61.65 GWG=0.25 ICWR=1
TWA=0.750 ROK=0.150 DELTC=0.060 UCOST= 127. SALV=  33.
PHIMX1=0.300 PHIMX2=0.300 PHIMXF=0.100 MUEMAX=0.600
BHN= 260.0, 260.0, 260.0 E= 0.300E+08 G= 0.115E+08 POIS=0.300 L= 0.500E+08 C= 0.830E+08
CALOCO= 2.5 LPC= 4.0 SPD=  7.0 EMPO= 6250.0 DYNBRK=1.000 RUNOUT=0.0005
OFFBAL=0.300 GWMIN= 0.150 DBUFF= 0.330,-0.000 TRMSTF= 2655. TRMSLP=0.516
ADELTA=0.000 FDELTA= 0.000
A=0.320 FANGLE=62.50 SDFAC=0.430,1.130,1.130 FCRITS=  13.0
WRABR= 1.660 WRPLS= 2.500 BATP2= 1.000 BATP1= 0.333
CR= 11.50, 11.50,  1.30 K=  7.5 SUBT=  0.0 CW=-22.00,-22.00, -1.60 CW2FF= 20.00
CALABR=  1.00,  1.00,  0.75 CALPLF=  1.00,  1.00,  0.75 SWCAL=  1.00 THRSCL=  1.00
SECAL= 135. SUCAL= 500. MCYCAL= 0.500E+08 ONE=  1.00 CALCYC=  1.00
XMARGN=0.0100 CALFAT=100.00 MINER=  1.00 IOFF= 50.00 CN=-0.100E+01
FC= 0.000E+00, 0.000E+00 FL= 0.900E+00, 0.143E+02 BUFFS= 0.000E+00, 0.000E+00 IAM=1,1
VERSON= 16.08 BHNSAV= 260. SESAV= -1.00 GRDSAV= -0.58 LUBRIC=1 IRAIL=3 LOOP=  1
```

NUM		GRWT	XMGT	V	PO	WUE	R3	H
1	FORWARD 3 AXLE LOCOMOTIVE	372000.	0.70	30.0	31000.	5484.	20.00	90.00
2	FORWARD FREIGHT CAR	188000.	10.00	30.0	23500.	1995.	18.00	90.00
1	BACKHAUL 3 AXLE LOCOMOTIVE	372000.	0.35	30.0	31000.	5484.	20.00	90.00
2	BACKHAUL FREIGHT CAR	140000.	5.00	30.0	17500.	1995.	18.00	90.00

APPENDIX F.4

RMCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE FORWARD DIRECTION GRADE=-0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.36834	40.110	22439.	0.2148	-1.1643	0.0000	1.1839	22508.	23697.	33260.	32782.
RAIL 2	-0.03530	13.370	31078.	0.1551	-0.3883	0.0000	0.4182	31149.	32820.	33260.	32782.
HEAD 3	0.18417	26.740	26296.	0.2438	-0.7759	0.0000	0.8133	26466.	28036.	33260.	32782.
LOW 1	0.10557	40.110	31045.	-0.0853	-1.1613	0.0000	1.1645	31116.	32785.	33260.	32782.
RAIL 2	0.03530	13.370	31074.	-0.3941	-0.3883	0.0000	0.5033	31145.	32815.	33260.	32782.
HEAD 3	0.07036	26.740	31059.	-0.0544	-0.7740	0.0000	0.7761	31130.	32800.	33260.	32782.
GAGE 1	0.36834	40.110	14227.	-1.3563	-1.1829	-2.2723	2.8786	14294.	14523.		
FACE 2	-0.03530	13.370	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		
3	0.18417	26.740	8802.	-1.3410	-0.7884	-1.5144	2.1710	8868.	8963.		

RMCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 2: 188000. LB FREIGHT CAR FORWARD DIRECTION GRADE=-0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.33031	36.556	16902.	0.3435	-1.6395	0.0000	1.6752	16970.	17581.	25630.	24480.
RAIL 2	-0.09014	34.170	23548.	0.2350	-0.9916	0.0000	1.0198	23618.	24494.	25630.	24480.
LOW 1	0.14862	36.556	23545.	0.0706	-1.6350	0.0000	1.6365	23614.	24490.	25630.	24480.
RAIL 2	0.09006	34.170	23545.	-0.2272	-0.9908	0.0000	1.0165	23614.	24490.	25630.	24480.
GAGE 1	0.33031	36.556	12203.	-1.3775	-1.6687	-3.2056	3.8475	12268.	12362.		
FACE 2	-0.09014	34.170	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		

RMCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE BACKHAUL DIRECTION GRADE= 0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.34495	40.110	22946.	-1.7312	-1.1870	0.0000	2.0996	23014.	24233.	33260.	32782.
RAIL 2	-0.03592	13.370	31293.	-1.4042	-0.3952	0.0000	1.6522	31364.	33047.	33260.	32782.
HEAD 3	0.17248	26.740	26801.	0.2394	-0.7760	0.0000	0.8121	26871.	28303.	33260.	32782.
LOW 1	0.10763	40.110	30830.	-2.0265	-1.1840	0.0000	2.3470	30901.	32558.	33260.	32782.
RAIL 2	0.03592	13.370	31289.	-2.1225	-0.3952	0.0000	2.1895	31360.	33042.	33260.	32782.
HEAD 3	0.07036	26.740	31059.	-0.0608	-0.7740	0.0000	0.7764	31130.	32800.	33260.	32782.
GAGE 1	0.34495	40.110	15273.	-3.3329	-1.2060	-2.3166	4.2343	15340.	15582.		
FACE 2	-0.03592	13.370	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		
3	0.17248	26.740	8398.	-1.3455	-0.7884	-1.5145	2.1738	8462.	8551.		

RMCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 2: 140000. LB FREIGHT CAR BACKHAUL DIRECTION GRADE= 0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.32710	36.153	12629.	0.3414	-1.6279	0.0000	1.6633	12695.	13136.	19561.	18480.
RAIL 2	-0.08906	33.765	17536.	0.2467	-0.9798	0.0000	1.0103	17604.	18240.	19561.	18480.
LOW 1	0.14756	36.153	17533.	0.0686	-1.6233	0.0000	1.6248	17601.	18237.	19561.	18480.
RAIL 2	0.08906	33.765	17533.	-0.2357	-0.7791	0.0000	1.0071	17601.	18237.	19561.	18480.
GAGE 1	0.32710	36.153	9011.	-1.3804	-1.6568	-3.1827	3.8445	9076.	9129.		
FACE 2	-0.08906	33.765	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		

APPENDIX F.5

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE FORWARD DIRECTION GRADE--0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.36834	40.110	0.50000	-428.14	2374.77	22439.31	22569.	22508.	22497.	33260.	32782.
RAIL 2	-0.03330	13.370	0.00000	-438.56	1096.99	31078.68	31191.	31149.	32829.	33260.	32782.
HEAD 3	0.18417	26.740	0.50000	-589.40	1875.87	26595.55	26668.	26666.	28086.	33260.	32782.
LOW 1	0.16057	40.110	0.50000	340.81	3277.27	31044.64	31218.	31116.	32785.	33260.	32782.
RAIL 2	0.03330	13.370	0.00000	1113.30	1076.84	31075.45	31113.	31145.	32815.	33260.	32782.
HEAD 3	0.07936	26.740	0.50000	159.25	2185.23	31059.14	31136.	31130.	32800.	33260.	32782.
GAGE 1	0.36834	40.110	0.50000	666.84	-13811.53	8669.79	16289.	14294.	16523.		
FACE 2	-0.03330	13.370	0.00000	0.00	0.00	0.00	0.	0.	0.		
3	0.18417	26.740	0.50000	357.63	-7396.92	4468.04	8821.	8866.	8962.		

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 2: 133000. LB FREIGHT CAR FORWARD DIRECTION GRADE--0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.33031	54.558	0.50000	-527.72	2517.05	16782.28	17097.	16970.	17381.	25630.	24480.
RAIL 2	-0.09014	34.170	0.12180	-509.39	2122.54	23548.20	23647.	23618.	24494.	25630.	24480.
LOW 1	0.14862	54.558	0.50000	-151.16	3499.38	23544.84	23804.	23614.	24490.	25630.	24480.
RAIL 2	0.09006	34.170	0.12180	484.31	2120.45	23544.84	23645.	23614.	24490.	25630.	24480.
GAGE 1	0.33031	54.558	0.50000	434.43	-10297.31	6645.92	12263.	12268.	12362.		
FACE 2	-0.09014	34.170	0.12180	0.00	0.00	0.00	0.	0.	0.		

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 3: 146000. LB FREIGHT CAR BACKHAUL DIRECTION GRADE- 0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.32710	56.133	0.50000	-391.92	1868.73	12628.94	12772.	12695.	13134.	19361.	18480.
RAIL 2	-0.08706	33.765	0.12026	-393.28	1561.75	17533.89	17610.	17604.	18240.	19361.	18480.
LOW 1	0.14756	56.133	0.50000	-109.27	2587.26	17533.39	17724.	17601.	18237.	19361.	18480.
RAIL 2	0.08760	33.765	0.12026	376.05	1560.49	17533.39	17607.	17601.	18237.	19361.	18480.
GAGE 1	0.32710	56.133	0.50000	323.53	-7404.76	4706.96	9056.	9076.	9129.		
FACE 2	-0.08706	33.765	0.12026	0.00	0.00	0.00	0.	0.	0.		

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE BACKHAUL DIRECTION GRADE- 0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 BATTER (LB)	P2 BATTER (LB)
HIGH 1	0.34495	40.110	0.50000	3611.00	2475.78	22946.32	23360.	23016.	24233.	33260.	32782.
RAIL 2	-0.03292	13.370	0.00000	4563.31	1124.05	31293.07	31444.	31344.	33047.	33260.	32782.
HEAD 3	0.17248	26.740	0.50000	-583.20	1870.42	26880.63	26874.	26871.	28303.	33260.	32782.
LOW 1	0.13743	40.110	0.50000	5679.07	3318.05	30829.65	31523.	30901.	32528.	33260.	32782.
RAIL 2	0.03292	13.370	0.00000	6124.91	1123.89	31238.44	31962.	31346.	33042.	33260.	32782.
HEAD 3	0.07326	26.740	0.50000	171.67	2185.33	31059.14	31136.	31130.	32800.	33260.	32782.
GAGE 1	0.34495	40.110	0.50000	1202.14	-13112.15	7887.74	15349.	15340.	15552.		
FACE 2	-0.03292	13.370	0.00000	0.00	0.00	0.00	0.	0.	0.		
3	0.17248	26.740	0.50000	342.35	-7248.19	4262.96	8416.	8462.	8551.		

APPENDIX F.6(A)

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE FORWARD DIRECTION GRADE=-0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.34834	46.110	0.50000	-438.14	2374.77	32439.31	32549.	32508.	32497.	33240.	32782.
RAIL 2	-0.03530	13.370	0.00000	-438.26	1396.79	31078.38	31101.	31149.	31820.	33246.	32782.
HEAD 3	0.18417	26.740	0.50000	-589.40	1875.87	24595.25	24648.	24646.	25086.	33240.	32782.
LOW 1	0.10557	46.110	0.50000	240.81	3277.27	31044.64	31118.	31116.	32785.	33240.	32782.
RAIL 2	0.03530	13.370	0.00000	1113.30	1696.84	31073.45	31113.	31145.	32815.	33240.	32782.
HEAD 3	0.07034	26.740	0.50000	159.35	2185.23	31059.14	31134.	31139.	32800.	33240.	32782.
BASE 1	0.34834	46.110	0.50000	444.84	-13811.23	6689.79	14289.	14294.	14523.		
FACE 2	-0.03530	13.370	0.00000	0.00	0.00	0.00	0.	0.	0.		
3	0.18417	26.740	0.50000	357.43	-7576.92	4448.04	8821.	8866.	8962.		

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.34834	46.110	22439.	0.2148	-1.1643	0.3000	1.1839	32508.	32497.	33240.	32782.
RAIL 2	-0.03530	13.370	31078.	0.1951	-0.3883	0.0000	0.4182	31149.	32820.	33246.	32782.
HEAD 3	0.18417	26.740	24596.	0.2438	-0.7759	0.0000	0.8133	24646.	25086.	33240.	32782.
LOW 1	0.10557	46.110	31045.	-0.0823	-1.1613	0.0000	1.1645	31116.	32785.	33240.	32782.
RAIL 2	0.03530	13.370	31074.	-0.3941	-0.3883	0.0000	0.5533	31145.	32815.	33240.	32782.
HEAD 3	0.07034	26.740	31059.	-0.0544	-0.7748	0.0000	0.7761	31130.	32800.	33240.	32782.
BASE 1	0.34834	46.110	16227.	-1.3563	-1.1829	-2.2723	2.8986	14294.	14523.		
FACE 2	-0.03530	13.370	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		
3	0.18417	26.740	8802.	-1.3418	-0.7884	-1.5144	2.1710	8866.	8962.		

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 4 08-APR-82
VEHICLE NUMBER 2: 188000. LB FREIGHT CAR FORWARD DIRECTION GRADE=-0.34 %

AXLE	L/V	ANGLE OF ATTACK (MIN)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.33031	56.558	0.50000	-327.72	2319.05	16722.28	17097.	16970.	17581.	23640.	24480.
RAIL 2	-0.09014	34.176	0.15180	-509.39	2122.54	23548.28	23649.	23618.	24494.	23630.	24480.
LOW 1	0.14862	56.558	0.50000	-151.16	3499.38	23544.84	23804.	23614.	24490.	23630.	24480.
RAIL 2	0.09004	34.176	0.15180	486.31	2120.45	23544.84	23645.	23614.	24490.	23630.	24480.
BASE 1	0.33031	56.558	0.50000	434.43	-18297.31	6645.92	12363.	12268.	12362.		
FACE 2	-0.09014	34.176	0.15180	0.00	0.00	0.00	0.	0.	0.		

AXLE	L/V	ANGLE OF ATTACK (MIN)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.33031	56.558	16702.	0.3435	-1.4394	0.0000	1.4722	16970.	17581.	23640.	24480.
RAIL 2	-0.09014	34.176	23548.	0.2330	-0.9916	0.0000	1.0198	23618.	24494.	23630.	24480.
LOW 1	0.14862	56.558	23545.	0.0704	-1.4330	0.0000	1.4343	23614.	24490.	23630.	24480.
RAIL 2	0.09004	34.176	23545.	-0.2272	-0.9908	0.0000	1.0165	23614.	24490.	23630.	24480.
BASE 1	0.33031	56.558	12203.	-1.3713	-1.4487	-3.2054	3.8673	12268.	12362.		
FACE 2	-0.09014	34.176	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		

APPENDIX F.6(B)

NUCN RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE BACKHAUL DIRECTION GRADE= 0.34 %

AXLE	L/V	ANGLE OF ATTACK (RAD)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.34495	40.110	0.50000	3611.90	2473.78	22746.32	23360.	23016.	24233.	32760.	32782.
RAIL 2	-0.03292	13.370	0.00000	4543.31	1121.32	31293.09	31644.	31364.	33047.	33260.	32782.
MEAD 3	0.17248	26.740	0.50000	-583.50	1870.42	24830.43	24874.	24871.	26303.	33260.	32782.
LOW 1	0.10763	40.110	0.50000	3679.87	3318.85	30829.65	31223.	30991.	32338.	33260.	32782.
RAIL 2	0.03292	13.370	0.00000	6124.91	1123.89	31288.66	31907.	31360.	33042.	33260.	32782.
MEAD 3	0.07036	26.740	0.50000	171.67	2185.33	31059.16	31136.	31130.	32860.	33260.	32782.
BASE 1	0.34495	40.110	0.50000	1202.16	-13112.15	7887.76	15349.	15340.	15352.		
FACE 2	-0.03292	13.370	0.00000	0.00	0.00	0.00	0.	0.	0.		
3	0.17248	26.740	0.50000	342.35	-7248.19	4262.74	8416.	8462.	8321.		

AXLE	L/V	ANGLE OF ATTACK (RAD)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.34495	40.110	22946.	-1.7312	-1.1870	0.0000	2.0990	23016.	24233.	32760.	32782.
RAIL 2	-0.03292	13.370	31293.	-1.4642	-0.3902	0.0000	1.4222	31364.	33047.	33260.	32782.
MEAD 3	0.17248	26.740	24801.	0.2394	-0.7760	0.0000	0.8121	24871.	26303.	33260.	32782.
LOW 1	0.10763	40.110	30830.	-2.0245	-1.1840	0.0000	2.3470	30901.	32338.	33260.	32782.
RAIL 2	0.03292	13.370	31289.	-1.1535	-0.3952	0.0000	2.1893	31360.	33042.	33260.	32782.
MEAD 3	0.07036	26.740	31059.	-0.0668	-0.7740	0.0000	0.7744	31130.	32830.	33260.	32782.
BASE 1	0.34495	40.110	15273.	-3.3329	-1.2960	-2.3166	4.2343	15340.	15352.		
FACE 2	-0.03292	13.370	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		
3	0.17248	26.740	8398.	-1.3405	-0.7884	-1.3145	2.1738	8462.	8321.		

NUCN RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-82
VEHICLE NUMBER 2: 140000. LB FREIGHT CAR BACKHAUL DIRECTION GRADE= 0.34 %

AXLE	L/V	ANGLE OF ATTACK (RAD)	LATERAL POSITION (IN)	HORIZONTAL FORCE (LB)	LATERAL FORCE (LB)	VERTICAL FORCE (LB)	OVERALL FORCE (LB)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.32710	36.153	0.50000	-391.92	1848.73	12628.94	12772.	12693.	13134.	19561.	18482.
RAIL 2	-0.08906	33.765	0.12826	-393.28	1561.73	17330.89	17616.	17604.	18249.	19561.	18482.
LOW 1	0.14736	36.153	0.50000	-189.27	2587.26	17333.39	17724.	17681.	18237.	19561.	18480.
RAIL 2	0.08906	33.765	0.12826	376.05	1560.49	17333.39	17607.	17681.	18237.	19561.	18480.
BASE 1	0.32710	36.153	0.50000	323.32	-7604.76	4996.96	9856.	9876.	9129.		
FACE 2	-0.08906	33.765	0.12826	0.00	0.00	0.00	0.	0.	0.		

AXLE	L/V	ANGLE OF ATTACK (RAD)	NORMAL FORCE (LB)	HORIZONTAL CREEP (%)	LATERAL CREEP (%)	VERTICAL CREEP (%)	TOTAL CREEP (%)	HIGH FREQ FORCE (LB)	LOW FREQ FORCE (LB)	P1 RATTER (LB)	P2 RATTER (LB)
HIGH 1	0.32710	36.153	12629.	0.3414	-1.4279	0.0000	1.6433	12693.	13134.	19561.	18489.
RAIL 2	-0.08906	33.765	17336.	0.2467	-0.9798	0.0000	1.0103	17604.	18249.	19561.	18482.
LOW 1	0.14736	36.153	17333.	0.0686	-1.4233	0.0000	1.4248	17681.	18237.	19561.	18480.
RAIL 2	0.08906	33.765	17333.	-0.2359	-0.9791	0.0000	1.0371	17681.	18237.	19561.	18480.
BASE 1	0.32710	36.153	9811.	-1.3904	-1.4548	-3.1827	3.8445	9876.	9129.		
FACE 2	-0.08906	33.765	0.	0.0000	0.0000	0.0000	0.0000	0.	0.		

APPENDIX F.7(A)

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NUCN RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL        RUN 1
VEHICLE NUMBER 1:  372000. LB  3 AXLE LOCOMOTIVE
                                                  BACKHAUL DIRECTION    08-APR-82
                                                                        GRADE= 0.34 %
RAIL WEAR:

   AXLE      TOTAL CREEP (%)   FRICTION COEFF   LIMITING FRICTION   MAX STRESS (KPSI)   PLASTIC FLOW THRESHOLD (KPSI)   BRINELL HARDNESS   WEAR RATE (IN/MMGT)   PLASTIC FLOW RATE (IN/MMGT)   FLOW TO WEAR (RATIO)   TOTAL MECH WEAR (IN/MMGT)   WITH FALSE FLANGING (IN/MMGT)
HIGH 1      2.0990
RAIL 2      1.4522          0.1900            0.3000              139.91              97.12                 260.0          0.0003248          0.0001422              0.4379          0.0003173
HEAD 3      0.8121          0.0738            0.3000              155.16             101.99                 260.0          0.0003122          0.0002712              0.8684          0.0005834                  N
                                                                  167.39             111.16                 260.0          0.0001591          0.0001423              0.8945          0.0003014                  P
LOW  1      2.3478                                                                                                                                                                                                  N
RAIL 2      2.1892          0.2133            0.3000              124.37              94.41                 260.0          0.0004915          0.0003181              0.4469          0.0008099          0.0012334  N
HEAD 3      0.7764          0.0764            0.3000              133.15              96.13                 260.0          0.0004484          0.0003141              0.7004          0.0007424          0.0007424  N
                                                                  134.77             111.33                 260.0          0.0001652          0.0002914              1.2174          0.0003876          0.0004679  N
GAGE 1      4.2343
FACE 2      0.0000          0.1000            0.1000              182.03              2.72                  260.0          0.0016389          0.0002587              0.2014          0.0012897                  N
     3      2.1738          0.0639            0.1000              120.62             149.14                 260.0          0.0000000          0.0003000              0.6000          0.0003000                  N
FALSE FLANGING:          PROBABILITY                                                112.11                 260.0          0.0002137          0.0000635              0.2943          0.0002792                  N
LOW  1                    0.3026305
RAIL 2                    0.0000000                                 227.93              94.01                                                                                                                   N
HEAD 3                    0.1034234                                 229.83              96.13                                                                                                                   N
                                                                    228.49             111.33                                                                                                                   N
WEAR AND BATTER:                                                                                                 0.0009719          0.0012375              1.2733          0.0022694
                                                                                                                 0.0008743          0.0012419              1.4202          0.0021162                  N
                                                                                                                 0.0002716          0.0010321              3.7995          0.0013037                  N
CONTACT                  PER MMGT                                                                                                                                                                               N
                        WEAR      BATTER                    PER YEAR                                                                                                                                            N
                     (IN/MMGT) (IN/MMGT)                  WEAR      BATTER                  PER 1000 CARS
HIGH RAIL HEAD      0.0020042 0.0006182                (IN/YR)   (IN/YR)                 WEAR      BATTER
LOW RAIL HEAD       0.0049195 0.0009397              0.0009812 0.0002164             (IN/KCAR) (IN/KCAR)
GAGE FACE           0.0021378                        0.0017218 0.0003359             0.0003216 0.0001150
                    --------- ---------              0.0010982                       0.0009150 0.0001782
LIFE                    130.1   318.1 (MMGT)         --------- ---------             0.0002834
                                                          394.6   980.8 (YR)        --------- ---------
                                                                                        742.49   1719.18 (1000 CARS)

NUCN RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL        RUN 2
VEHICLE NUMBER 2:  140000. LB  FREIGHT CAR
                                                  BACKHAUL DIRECTION    08-APR-82
                                                                        GRADE= 0.34 %
RAIL WEAR:

   AXLE      TOTAL CREEP (%)   FRICTION COEFF   LIMITING FRICTION   MAX STRESS (KPSI)   PLASTIC FLOW THRESHOLD (KPSI)   BRINELL HARDNESS   WEAR RATE (IN/MMGT)   PLASTIC FLOW RATE (IN/MMGT)   FLOW TO WEAR (RATIO)   TOTAL MECH WEAR (IN/MMGT)   WITH FALSE FLANGING (IN/MMGT)
HIGH 1      1.6433
RAIL 2      1.8183          0.1512            0.3000              117.32              81.87                 260.0          0.0003383          0.0000711              0.1328          0.0003094
                            0.0918            0.3000              131.14              88.99                 260.0          0.0004141          0.0001429              0.3476          0.0005288                  N
LOW  1      1.4248                                                                                                                                                                                                  N
RAIL 2      1.6871          0.1477            0.3000              131.14             102.29                 260.0          0.0004244          0.0001087              0.2561          0.0008332          0.0008339  N
                            0.0913            0.3000              131.14             109.03                 260.0          0.0004132          0.0001435              0.3474          0.0005267          0.0005267  N
SIDE 1      3.8443
FACE 2      0.0000          0.1000            0.1000              136.59             108.01                 260.0          0.0016332          0.0002602              0.1274          0.0019134
FALSE FLANGING:          PROBABILITY          0.1000               2.31              120.92                 260.0          0.0000000          0.0000000              0.0000          0.0000000                  N
LOW  1                    0.0016145                                                                                                                                                                               N
RAIL 2                    0.0000000                                 193.35             102.29                                                                                                                   N
                                                                    193.35             109.03                                                                                                                   N
WEAR AND BATTER:                                                                                                 0.0011499          0.0013132              1.1420          0.0024631
                                                                                                                 0.0007336          0.0011784              1.6749          0.0018826                  N
CONTACT                  PER MMGT                                                                                                                                                                               N
                        WEAR      BATTER                    PER YEAR                                                                                                                                            N
                     (IN/MMGT) (IN/MMGT)                  WEAR      BATTER                  PER 1000 CARS
HIGH RAIL HEAD      0.0023353 0.0002771                (IN/YR)   (IN/YR)                 WEAR      BATTER
LOW RAIL HEAD       0.0027352 0.0002948              0.0116765 0.0014833             (IN/KCAR) (IN/KCAR)
GAGE FACE           0.0020267                        0.0139233 0.0014739             0.0001435 0.0000296
                    --------- ---------              0.0191324                       0.0001930 0.0000294
LIFE                    167.9   339.3 (MMGT)         --------- ---------             0.0002679
                                                           33.5    67.9 (YR)        --------- ---------
                                                                                       2395.01   4849.44 (1000 CARS)
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APPENDIX F.7(B)

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AHCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL    RUN 8                    08-APR-82
VEHICLE NUMBER  1:   372000. LB   3 AXLE LOCOMOTIVE      BACKHAUL DIRECTION   GRADE- 0.34 %

RAIL WEAR:
                 TOTAL    FRICTION   LIMITING     MAX    PLASTIC FLOW  BRINELL   WEAR     PLASTIC FLOW    FLOW      TOTAL     WITH FALSE
    AXLE         CREEP    COEFF      FRICTION     STRESS  THRESHOLD    HARDNESS  RATE        RATE         TO WEAR   MECH WEAR  FLANGING
                   (%)                            (KPSI)    (KPSI)               (IN/MMGT) (IN/MMGT)    (RATIO)  (IN/MMGT) (IN/MMGT)
HIGH 1          2.0990     0.1900     0.3000      139.91     97.12      260.0   0.0003548 0.0001625    0.4579   0.0003173          M
RAIL 2          1.6522     0.1502     0.3000      125.16    101.99      260.0   0.0003122 0.0002712    0.8684   0.0003834          M
HEAD 3          0.9121     0.0738     0.3000      147.35    111.16      260.0   0.0001591 0.0001423    0.8945   0.0002314          M

LOW  1          2.3470     0.2133     0.3000      154.39     94.41      260.0   0.0004913 0.0003181    0.6448   0.0008299 0.0012334 M
RAIL 2          2.1893     0.1990     0.3000      135.15     98.13      260.0   0.0004481 0.0003141    0.7064   0.0007624 0.0007624 M
HEAD 3          0.7744     0.0704     0.3000      154.77    111.55      260.0   0.0001603 0.0002016    1.2194   0.0002479 0.0002479 M

GAGE 1          4.2343     0.1000     0.1000      182.03    108.01      260.0   0.0010389 0.0002587    0.2414   0.0012897          M
FACE 2          0.0000     0.0000     0.1000        2.72    120.02      260.0   0.0000000 0.0000000    0.0000   0.0000000          M
     3          2.1738     0.0639     0.1000      149.14    112.11      260.0   0.0002137 0.0000435    0.2043   0.0002792          M
FALSE FLANGING:  PROBABILITY
LOW  1                     0.3026305              227.93     94.41              0.0009719 0.0012375    1.2733   0.0022094          M
RAIL 2                     0.0000000              229.05     98.13              0.0008743 0.0012419    1.4205   0.0021162          M
HEAD 3                     0.1034234              228.49    111.55              0.0002716 0.0010321    3.7995   0.0013037          M

WEAR AND BATTER:
                          PER MMGT                      PER YEAR                    PER 1000 CARS
CONTACT                   WEAR      BATTER              WEAR      BATTER            WEAR      BATTER
                          (IN/MMGT) (IN/MMGT)           (IN/YR)   (IN/YR)           (IN/KCAR) (IN/KCAR)
HIGH RAIL HEAD            0.0020042 0.0006182           0.0009815 0.0002144         0.0005216 0.0001150
LOW RAIL HEAD             0.0049195 0.0009597           0.0017218 0.0003359         0.0009126 0.0001785
GAGE FACE                 0.0031378                     0.0010982                   0.0005836
                          --------- ---------           --------- ---------         --------- ---------
LIFE                        138.1     318.1 (MMGT)        394.6     908.8 (YR)        742.49   1710.18 (1000 CARS)


AHCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL    RUN 8                    08-APR-82
VEHICLE NUMBER  2:   140000. LB   FREIGHT CAR           BACKHAUL DIRECTION   GRADE- 0.34 %

RAIL WEAR:
                 TOTAL    FRICTION   LIMITING     MAX    PLASTIC FLOW  BRINELL   WEAR     PLASTIC FLOW    FLOW      TOTAL     WITH FALSE
  AXLE           CREEP    COEFF      FRICTION     STRESS  THRESHOLD    HARDNESS  RATE        RATE         TO WEAR   MECH WEAR  FLANGING
                   (%)                            (KPSI)    (KPSI)               (IN/MMGT) (IN/MMGT)    (RATIO)  (IN/MMGT) (IN/MMGT)
HIGH 1          1.6633     0.1512     0.3000      117.55    101.87      260.0   0.0002385 0.0000711    0.1220   0.0006096          M
RAIL 2          1.0103     0.0918     0.3000      131.14    108.99      260.0   0.0004141 0.0001439    0.3476   0.0005580          M

LOW  1          1.4248     0.1477     0.3000      131.14    102.29      260.0   0.0004244 0.0002087    0.7341   0.0006333 0.0006333 M
RAIL 2          1.0071     0.0915     0.3000      131.14    109.03      260.0   0.0004132 0.0001435    0.3474   0.0005567 0.0005567 M

GAGE 1          3.8443     0.1000     0.1000      156.39    108.01      260.0   0.0016332 0.0002692    0.1574   0.0019134          M
FACE 2          0.0000     0.0000     0.1000        2.31    120.02      260.0   0.0000000 0.0000000    0.0000   0.0000000          M
FALSE FLANGING:  PROBABILITY
LOW  1                     0.0016145              193.25    102.29              0.0011499 0.0013132    1.1420   0.0024631          M
RAIL 2                     0.0000000              193.25    109.03              0.0007034 0.0011784    1.6749   0.0018818          M

WEAR AND BATTER:
                          PER MMGT                      PER YEAR                    PER 1000 CARS
CONTACT                   WEAR      BATTER              WEAR      BATTER            WEAR      BATTER
                          (IN/MMGT) (IN/MMGT)           (IN/YR)   (IN/YR)           (IN/KCAR) (IN/KCAR)
HIGH RAIL HEAD            0.0023323 0.0002971           0.0011745 0.0001453         0.0001635 0.0000208
LOW RAIL HEAD             0.0027322 0.0003948           0.0013758 0.0001739         0.0001918 0.0000244
GAGE FACE                 0.0028267                     0.0014234                   0.0002679
                          --------- ---------           --------- ---------         --------- ---------
LIFE                        167.7     339.3 (MMGT)        33.3      67.9 (YR)        2395.81   4819.66 (1000 CARS)
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APPENDIX F.8(A)

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RKCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL     RUN 1                    08-APR-82
VEHICLE NUMBER 1:  372000. LB   3 AXLE LOCOMOTIVE       FORWARD DIRECTION   GRADE=-0.34 %

RAIL BATTER:
          TOTAL    FRICTION  LIMITING     MAX   PLASTIC FLOW BRINELL   WEAR   PLASTIC FLOW   FLOW      TOTAL    WITH FALSE
  AXLE    CREEP    COEFF     FRICTION     STRESS THRESHOLD   HARDNESS  RATE       RATE        TO WEAR   WEAR     FLANGING
           (%)                             (KPSI)  (KPSI)             (IN/MMBT)  (IN/MMBT)   (RATIO)   (IN/MMBT) (IN/MMBT)
HIGH 1    1.1839    0.1376    0.3000      134.74   107.10    260.0    0.0000000  0.0000724   100.0000  0.0000724          M
RAIL 2    0.4182    0.0280    0.3000      134.74   115.45    260.0    0.0000000  0.0000792   100.0000  0.0000792          M
WEAR 3    0.8133    0.0737    0.3000      134.74   111.14    260.0    0.0000000  0.0000814   100.0000  0.0000814          M

LOW  1    1.1645    0.1059    0.3000      134.74   107.31    260.0    0.0000000  0.0000917   100.0000  0.0000917  0.0000231 M
RAIL 2    0.5333    0.0503    0.3000      134.74   113.98    260.0    0.0000000  0.0000742   100.0000  0.0000742  0.0000742 M
WEAR 3    0.7761    0.0703    0.3000      134.74   111.55    260.0    0.0000000  0.0000805   100.0000  0.0000805  0.0001237 M
FALSE FLANGING:   PROBABILITY
LOW  1            0.3702916              228.45   107.31              0.0000000  0.0004337   100.0000  0.0004337          M
RAIL 2            0.0000000              228.45   113.98              0.0000000  0.0004934   100.0000  0.0004934          M
WEAR 3            0.1300744              228.45   111.55              0.0000000  0.0004125   100.0000  0.0004125          M

WEAR AND BATTER:
                        PER MMBT                  PER YEAR                  PER 1000 CARS
CONTACT                 WEAR      BATTER          WEAR      BATTER          WEAR      BATTER
                        (IN/MMBT) (IN/MMBT)       (IN/YR)   (IN/YR)         (IN/KCAR) (IN/KCAR)
HIGH RAIL HEAD          0.0017742 0.0004891       0.0012420 0.0003424       0.0003368 0.0000910
LOW RAIL HEAD           0.0032977 0.0008362       0.0023084 0.0005853       0.0006134 0.0001555
GAGE FACE               0.0021395                 0.0014977                 0.0003979
                        --------- ---------       --------- ---------       --------- ---------
LIFE                      298.0     432.9 (MMBT)      297.1     618.5 (YR)      1118.26   2327.57 (1000 CARS)


RKCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL     RUN 1                    08-APR-82
VEHICLE NUMBER 2:  188500. LB   FREIGHT CAR             FORWARD DIRECTION   GRADE=-0.34 %

RAIL BATTER:
          TOTAL    FRICTION  LIMITING     MAX   PLASTIC FLOW BRINELL   WEAR   PLASTIC FLOW   FLOW      TOTAL    WITH FALSE
  AXLE    CREEP    COEFF     FRICTION     STRESS THRESHOLD   HARDNESS  RATE       RATE        TO WEAR   WEAR     FLANGING
           (%)                             (KPSI)  (KPSI)             (IN/MMBT)  (IN/MMBT)   (RATIO)   (IN/MMBT) (IN/MMBT)
HIGH 1    1.6722    0.1523    0.3000      144.66   101.74    260.0    0.0000000  0.0001323   100.0000  0.0001323          M
RAIL 2    1.0198    0.0927    0.3000      144.66   108.89    260.0    0.0000000  0.0001624   100.0000  0.0001624          M

LOW  1    1.4345    0.1488    0.3000      144.66   102.16    260.0    0.0000000  0.0001305   100.0000  0.0001305  0.0001491 M
RAIL 2    1.0145    0.0924    0.3000      144.66   108.93    260.0    0.0000000  0.0001622   100.0000  0.0001622  0.0001622 M
FALSE FLANGING:   PROBABILITY
LOW  1            0.0392365              213.18   102.16              0.0000000  0.0006366   100.0000  0.0006366          M
RAIL 2            0.0000000              213.18   108.93              0.0000000  0.0005767   100.0000  0.0005767          M

WEAR AND BATTER:
                        PER MMBT                  PER YEAR                  PER 1000 CARS
CONTACT                 WEAR      BATTER          WEAR      BATTER          WEAR      BATTER
                        (IN/MMBT) (IN/MMBT)       (IN/YR)   (IN/YR)         (IN/KCAR) (IN/KCAR)
HIGH RAIL HEAD          0.0024048 0.0004493       0.0245484 0.0044934       0.0032207 0.0000441
LOW RAIL HEAD           0.0031709 0.0003246       0.0317093 0.0032459       0.0002981 0.0000493
GAGE FACE               0.0027740                 0.0277297                 0.0003548
                        --------- ---------       --------- ---------       --------- ---------
LIFE                      159.6     314.6 (MMBT)       16.0      31.5 (YR)      1697.79   3346.83 (1000 CARS)
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APPENDIX F.8(B)

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 1 08-APR-02
VEHICLE NUMBER 1: 372000. LB 3 AXLE LOCOMOTIVE BACKHAUL DIRECTION GRADE= 0.34 %

RAIL BATTER:

AXLE	TOTAL CREEP (%)	FRICTION COEFF	LIMITING FRICTION	MAX STRESS (KPSI)	PLASTIC FLOW THRESHOLD (KPSI)	BRINELL HARDNESS	WEAR RATE (IN/MMGT)	PLASTIC FLOW RATE (IN/MMGT)	FLOW TO WEAR (RATIO)	TOTAL MECH WEAR (IN/MMGT)	WITH FALSE FLANGING (IN/MMGT)	
HIGH 1	2.0990	0.1958	0.3000	134.74	97.12	260.0	0.0000000	0.0001288	100.0000	0.0001288		M
RAIL 2	1.4322	0.1302	0.3000	134.74	101.99	260.0	0.0000000	0.0001047	100.0000	0.0001047		M
HEAD 3	0.8121	0.0738	0.3000	134.74	111.16	260.0	0.0000000	0.0000814	100.0000	0.0000814		M
LOW 1	2.3470	0.2133	0.3000	134.74	94.41	260.0	0.0000000	0.0001289	100.0000	0.0001289	0.0002412	M
RAIL 2	2.1895	0.1990	0.3000	134.74	96.13	260.0	0.0000000	0.0001237	100.0000	0.0001237	0.0001237	M
HEAD 3	0.7764	0.0706	0.3000	134.74	111.33	260.0	0.0000000	0.0000805	100.0000	0.0000805	0.0001149	M
FALSE FLANGING:	PROBABILITY											
LOW 1		0.3026305		228.45	94.41		0.0000000	0.0003000	100.0000	0.0003000		M
RAIL 2		0.0000000		228.45	96.13		0.0000000	0.0004910	100.0000	0.0004910		M
HEAD 3		0.1034234		228.45	111.33		0.0000000	0.0004125	100.0000	0.0004125		M

WEAR AND BATTER:

CONTACT	PER MMGT WEAR (IN/MMGT)	PER MMGT BATTER (IN/MMGT)	PER YEAR WEAR (IN/YR)	PER YEAR BATTER (IN/YR)	PER 1000 CARS WEAR (IN/KCAR)	PER 1000 CARS BATTER (IN/KCAR)	
HIGH RAIL HEAD	0.0028042	0.0006182	0.0069815	0.0015394	0.0002216	0.0001120	
LOW RAIL HEAD	0.0049193	0.0009397	0.0017218	0.0002339	0.0009130	0.0001703	
BARE FACE	0.0031378		0.0010982		0.0005834		
LIFE	136.1	318.1 (MMGT)	394.6	908.8 (YR)	742.49	1710.18 (1000 CARS)	

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 2 08-APR-02
VEHICLE NUMBER 2: 140000. LB FREIGHT CAR BACKHAUL DIRECTION GRADE= 0.34 %

RAIL BATTER:

AXLE	TOTAL CREEP (%)	FRICTION COEFF	LIMITING FRICTION	MAX STRESS (KPSI)	PLASTIC FLOW THRESHOLD (KPSI)	BRINELL HARDNESS	WEAR RATE (IN/MMGT)	PLASTIC FLOW RATE (IN/MMGT)	FLOW TO WEAR (RATIO)	TOTAL MECH WEAR (IN/MMGT)	WITH FALSE FLANGING (IN/MMGT)	
HIGH 1	1.4433	0.1312	0.3000	131.71	101.67	260.0	0.0000000	0.0000883	100.0000	0.0000883		M
RAIL 2	1.0103	0.0918	0.3000	131.71	108.99	260.0	0.0000000	0.0000692	100.0000	0.0000692		M
LOW 1	1.6248	0.1477	0.3000	131.71	102.29	260.0	0.0000000	0.0000844	100.0000	0.0000844	0.0000873	M
RAIL 2	1.0871	0.0915	0.3000	131.71	109.03	260.0	0.0000000	0.0000681	100.0000	0.0000681	0.0000681	M
FALSE FLANGING:	PROBABILITY											
LOW 1		0.0016145		194.11	102.29		0.0000000	0.0003369	100.0000	0.0003369		M
RAIL 2		0.0000000		194.11	109.03		0.0000000	0.0004823	100.0000	0.0004823		M

WEAR AND BATTER:

CONTACT	PER MMGT WEAR (IN/MMGT)	PER MMGT BATTER (IN/MMGT)	PER YEAR WEAR (IN/YR)	PER YEAR BATTER (IN/YR)	PER 1000 CARS WEAR (IN/KCAR)	PER 1000 CARS BATTER (IN/KCAR)	
HIGH RAIL HEAD	0.0023353	0.0002971	0.0116765	0.0014853	0.0001635	0.0000208	
LOW RAIL HEAD	0.0037852	0.0002948	0.0189228	0.0014739	0.0001929	0.0000206	
BARE FACE	0.0038267		0.0191336		0.0013479		
LIFE	167.7	339.3 (MMGT)	33.5	67.9 (YR)	2393.01	4849.44 (1000 CARS)	

APPENDIX F.9

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 0

08-APR-92

***** ENGINEERING RESULTS SUMMARY *****

HIGH RAIL TREAD WEAR =	0.038440	IN/YR	0.239584	IN/100 MMGT
LOW RAIL TREAD WEAR =	0.049665	IN/YR	0.309442	IN/100 MMGT
GAUGE FACE WEAR =	0.059469	IN/YR	0.370525	IN/100 MMGT
HIGH RAIL JOINT/WELD BATTER =	0.006737	IN/YR	0.041978	IN/100 MMGT
LOW RAIL JOINT/WELD BATTER =	0.007641	IN/YR	0.047607	IN/100 MMGT
HIGH RAIL FATIGUE LIFE =	1000.00	YR	14050.00	MMGT
LOW RAIL FATIGUE LIFE =	1000.00	YR	14050.00	MMGT
JOINT/WELD BATTER LIFE =	39.31	YR	326.81	MMGT
RAIL WEAR LIFE =	30.14	YR	163.14	MMGT

APPENDIX F.10

WEAR AND BATTER IN INCHES/100 MMGT

HI RAIL WEAR	LOW RAIL WEAR	GAGE FACE WEAR	HI RAIL BATTER	LOW RAIL BATTER
0.239584	0.309442	0.370525	0.041978	0.047607

RUN ID 08-APR-92

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN

APPENDIX F.11

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 0

WEB	DIR	HI RAIL WEAR (IN/MMGT)	LO RAIL WEAR (IN/MMGT)	GAGE FACE WEAR	HI RAIL BATTER (IN/MMGT)	LO RAIL BATTER (IN/MMGT)	WEAR LIFE (MMGT)	BATTER LIFE (MMGT)	CN WEIGHT
1	1	0.0017742	0.0032979	0.0021392	0.0004891	0.0008362	208.8	432.9	1.000
2	1	0.0024248	0.0031709	0.0027748	0.0004693	0.0008246	159.6	314.6	0.459
1	2	0.0028642	0.0049193	0.0031378	0.0006182	0.0009297	135.1	318.1	1.556
2	2	0.0023353	0.0037832	0.0038267	0.0002971	0.0002948	167.7	339.8	0.447

APPENDIX F.12

WEAR, BATTER, AND FATIGUE LIVES IN MMGT

WEAR LIFE	BATTER LIFE	HI RAIL FATIGUE	LOW RAIL FATIGUE
163.	326.	14050.	14050.

RUN ID 08-APR-92

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 0

APPENDIX F.13

WEAR LIFE IN MMGT AND WEAR RATES IN INCHES/100 MMGT

WEAR LIFE	HI RAIL WEAR	LOW RAIL WEAR	GAGE FACE WEAR
163.	0.239584	0.309442	0.370525

RUN ID 08-APR-92

RNCH RUNS FOR ILLUSTRATIVE EXAMPLES IN USER'S MANUAL RUN 0

APPENDIX F.14

***** ENGINEERING RESULTS SUMMARY *****

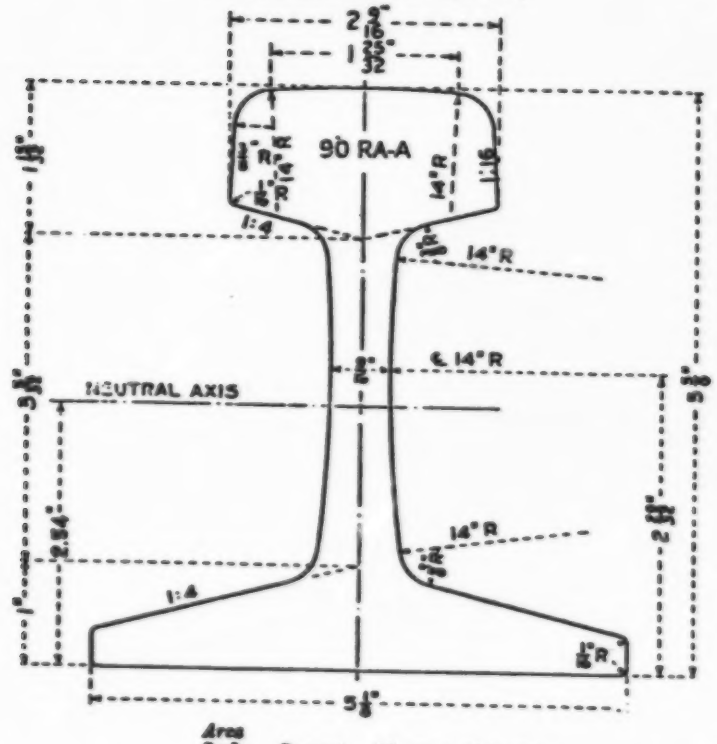
HIGH RAIL TREAD WEAR =	0.056285	IN/YR		
LOW RAIL TREAD WEAR =	0.071166	IN/YR		
GAUGE FACE WEAR =	0.071014	IN/YR		
HIGH RAIL JOINT/WELD BATTER =	0.056336	IN/YR		
LOW RAIL JOINT/WELD BATTER =	0.069191	IN/YR		
HIGH RAIL FATIGUE LIFE =	1000.00	YR	54000.00	MMGT
LOW RAIL FATIGUE LIFE =	1000.00	YR	54000.00	MMGT
JOINT/WELD BATTER LIFE =	7.63	YR	412.13	MMGT
RAIL WEAR LIFE =	7.54	YR	408.13	MMGT

***** LIFE AND COST SUMMARY *****

VEHICLE DELETED	WEAR LIFE (YR)	BATTER LIFE (YR)	HIGH RAIL FATIGUE (YR)	LOW RAIL FATIGUE (YR)	INCREMENTAL CHARGES DISTRIB-1 (CENTS/1000 GTM)	INCREMENTAL CHARGES DISTRIB-2 (CENTS/1000 GTM)	MARGINAL CHARGES DISTRIB-1 (CENTS/1000 GTM)	MARGINAL CHARGES DISTRIB-2 (CENTS/1000 GTM)
NOMINAL	7.54	7.63	1000.00	1000.00				
VEH 1 FORWARD	7.68	7.75	1000.00	1000.00	17.93	18.52	17.93	18.53
VEH 2 FORWARD	9.39	9.60	1000.00	1000.00	32.35	33.64	32.58	33.65
VEH 1 BACKHAUL	7.71	7.78	1000.00	1000.00	21.85	22.56	21.86	22.58
VEH 2 BACKHAUL	13.84	13.86	1000.00	1000.00	22.96	24.32	23.54	24.32

1962

(Reapproved without change 1962)



	Area Sq In	Percent
Head	3.19	36.3
Web	2.12	24.0
Base	3.51	39.7
Total	8.82	100.0

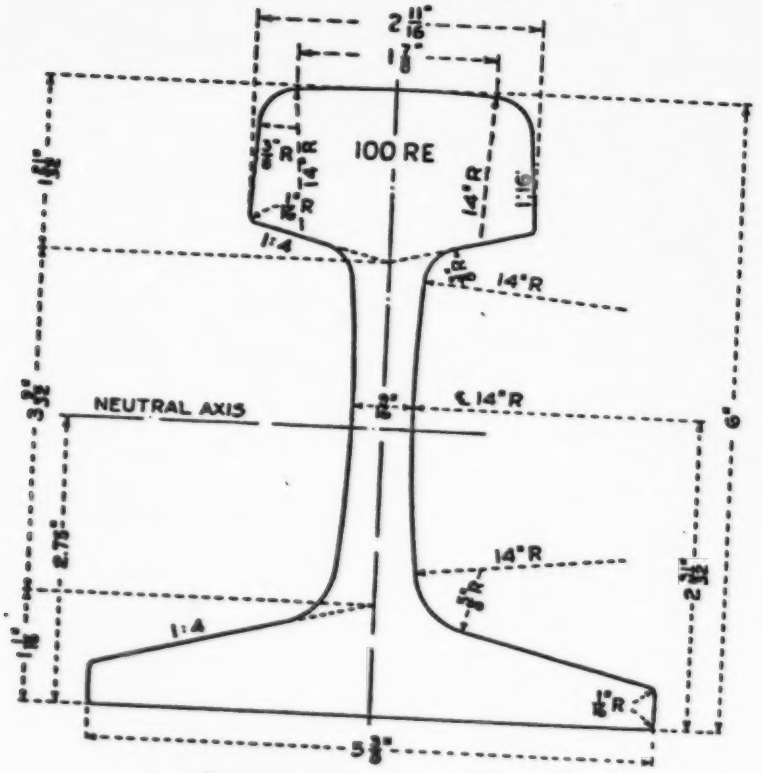
Moment of inertia	38.7
Section modulus, head	12.6
Section modulus, base	15.2
Ratio m.i. to area	4.39
Ratio s.m. head to area	1.43
Ratio height to base	1.10
Calculated weight, lb per yd	90.0

Fig. 1—90 RA-A rail section.

References, Vol. 16, 1915, pp. 397, 1117; Vol. 49, 1948, pp. 373, 614; Vol. 54, 1953, pp. 1177, 1413; Vol. 63, 1962, pp. 498, 768.

1962

(Reapproved without change 1962)



	Area Sq In	Percent
Head	3.80	38.2
Web	2.25	22.6
Base	3.90	39.2
Total	9.95	100.0

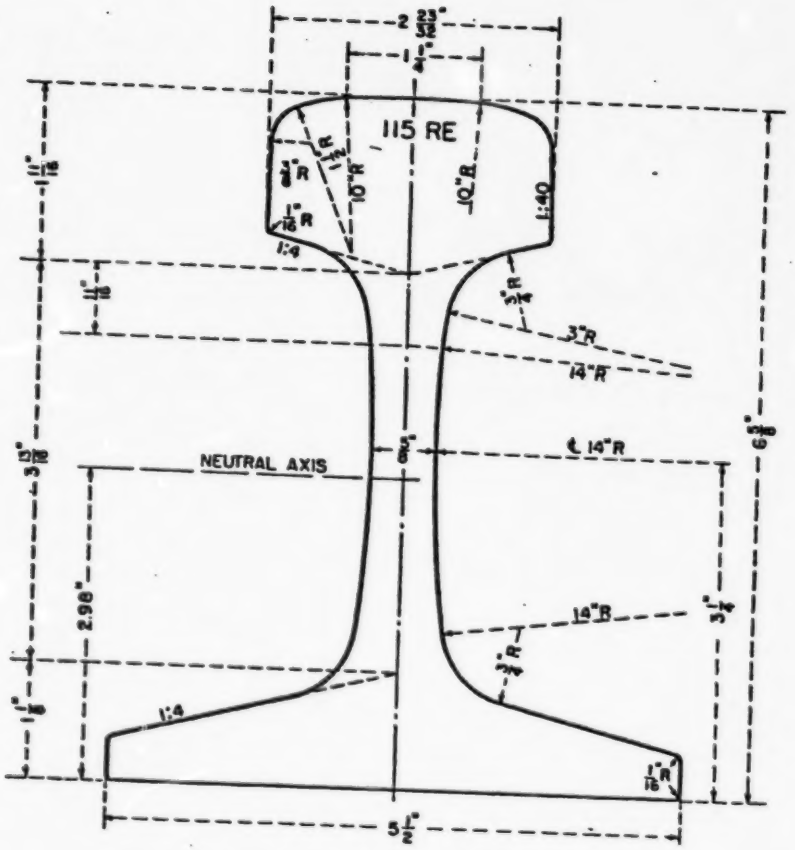
Moment of inertia	49.0
Section modulus, head	15.1
Section modulus, base	17.8
Ratio m.i. to area	4.92
Ratio s.m. head to area	1.52
Ratio height to base	1.12
Calculated weight, lb per yd	101.5

Fig. 2—100 RE rail section.

References, Vol. 16, 1915, pp. 398, 1117; Vol. 49, 1948, pp. 375, 614; Vol. 54, 1953, pp. 1177, 1413; Vol. 62, 1962, pp. 498, 768.

1962

(Reapproved without change 1962)



	Area Sq In	Percent
Head	3.91	34.8
Web	3.05	27.1
Base	4.29	38.1
Total	11.25	100.0

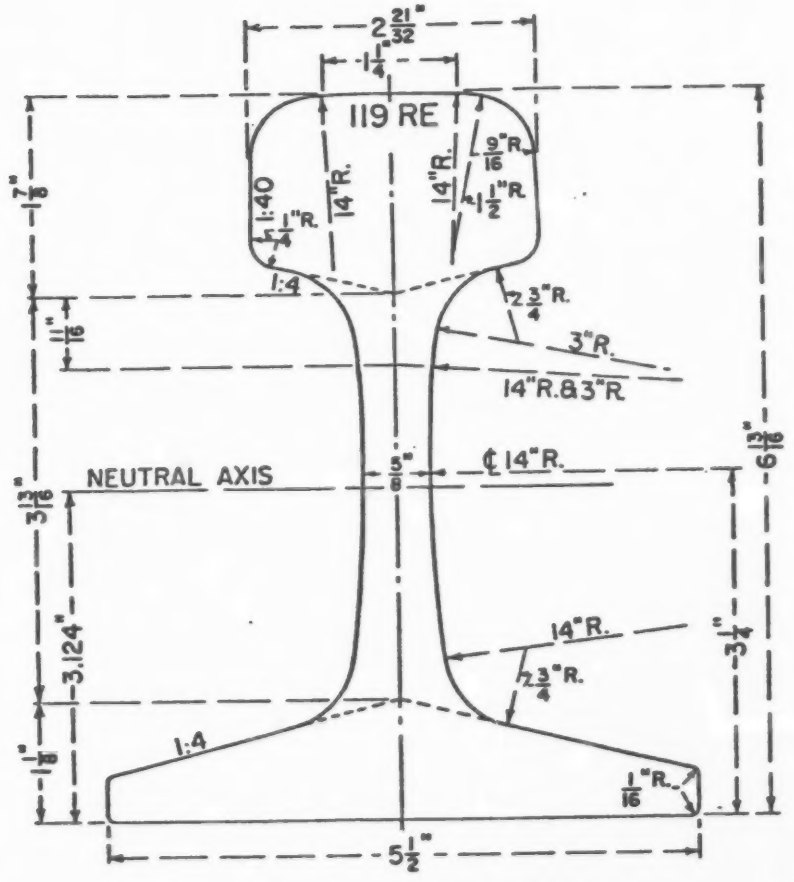
Moment of inertia	65.6
Section modulus, head	18.0
Section modulus, base	22.0
Ratio m.i. to area	5.83
Ratio s.m. head to area	1.60
Ratio height to base	1.20
Calculated weight, lb per yd	114.7

Fig. 3—115 RE rail section.

References, Vol. 16, 1915, pp. 399, 1117; Vol. 35, 1934, pp. 875, 1144; Vol. 38, 1937, pp. 251, 435; Vol. 48, 1947, pp. 660, 908; Vol. 54, 1953, pp. 1177, 1413; Vol. 63, 1962, pp. 458, 768.

1971

(Adopted 1971)



	Area Sq In	Percent
Head	4.32	37.1
Web	3.04	26.1
Base	4.29	36.8
Total	11.65	100.0

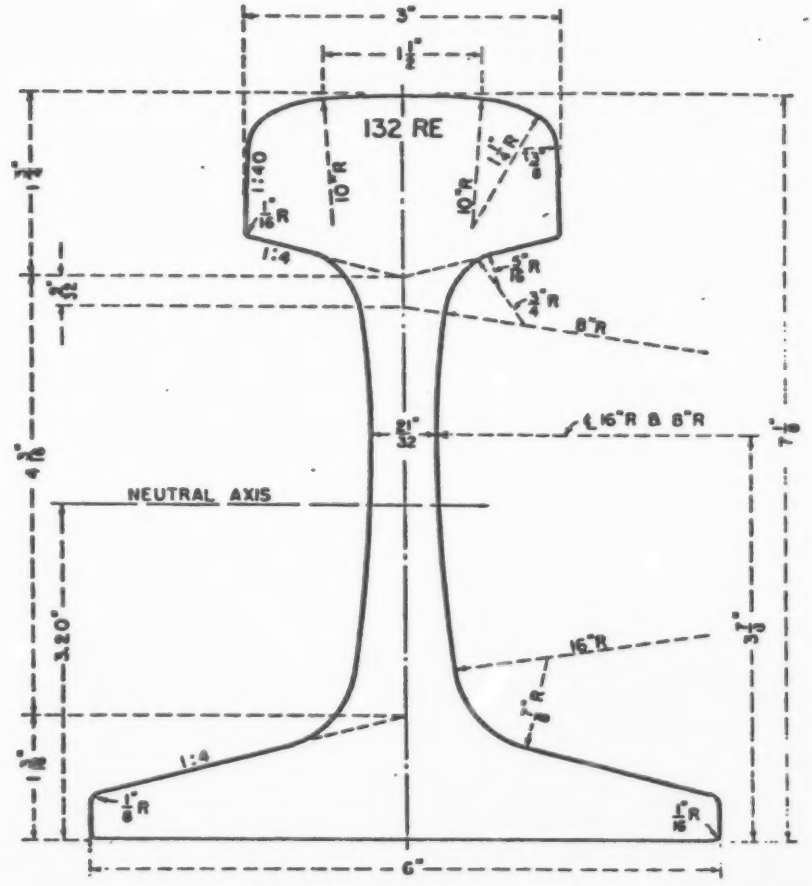
Moment of inertia	71.4
Section modulus, head	19.4
Section modulus, base	22.9
Ratio m.i. to area	6.13
Ratio s.m. head to area	1.70
Ratio height to base	1.24
Calculated weight, lb per yd	118.8

Fig.4—119 RE rail section.

References, Vol. 72, 1971, p. 160.

1962

(Reapproved without change 1962)



	Area Sq In	Percent
Head	4.42	34.1
Web	3.66	28.3
Base	4.87	37.6
Total	12.95	100.0

Moment of inertia	88.2
Section modulus, head	22.5
Section modulus, base	27.6
Ratio m.i. to area	6.81
Ratio s.m. head to area	1.74
Ratio height to base	1.15
Calculated weight, lb per yd	132.1

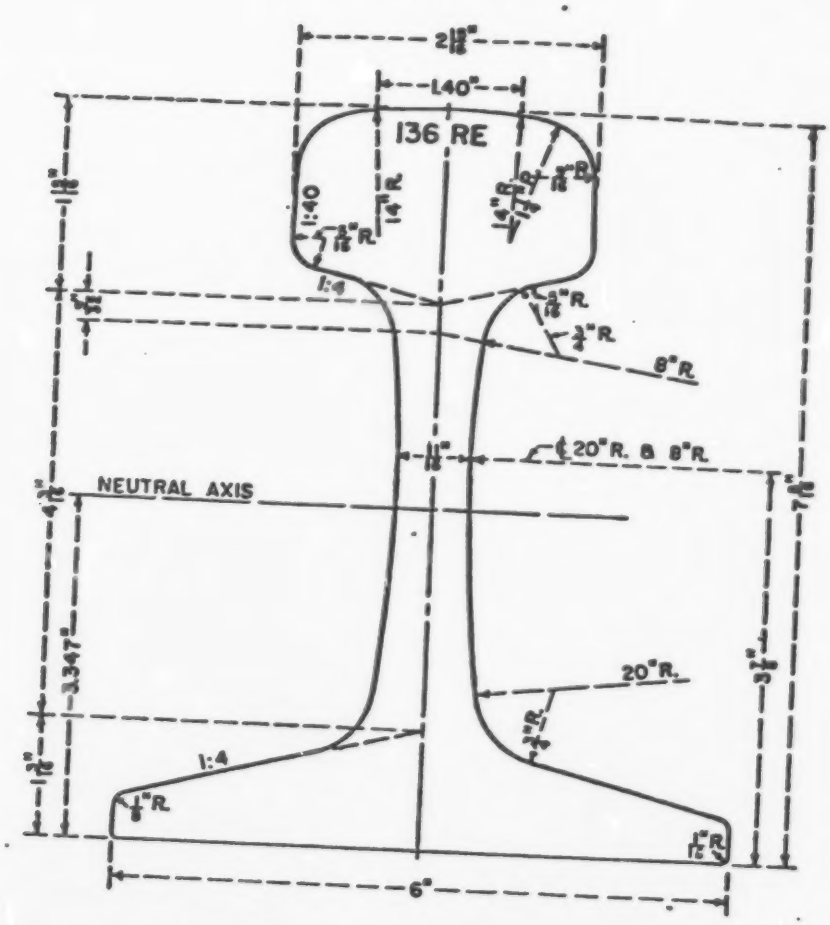
Fig. 5—132 RE rail section.

References, Vol. 21, 1920, p. 1455; Vol. 34, 1933, pp. 640, 874; Vol. 39, 1938, pp. 397, 803 Vol. 48, 1947, pp. 662, 908; Vol. 54, 1953, pp. 1177, 1413; Vol. 63, 1962, pp. 498, 768.

(1971)

1962

(Adopted 1962)



	Area Sq In	Percent
Head	4.86	36.4
Web	3.62	27.1
Base	4.87	36.5
Total	13.35	100.0

Moment of inertia	94.9
Section modulus, head	23.9
Section modulus, base	28.3
Ratio m.i. to area	7.11
Ratio s.m. head to area	1.79
Ratio height to base	1.22
Calculated weight, lb per yd	136.2

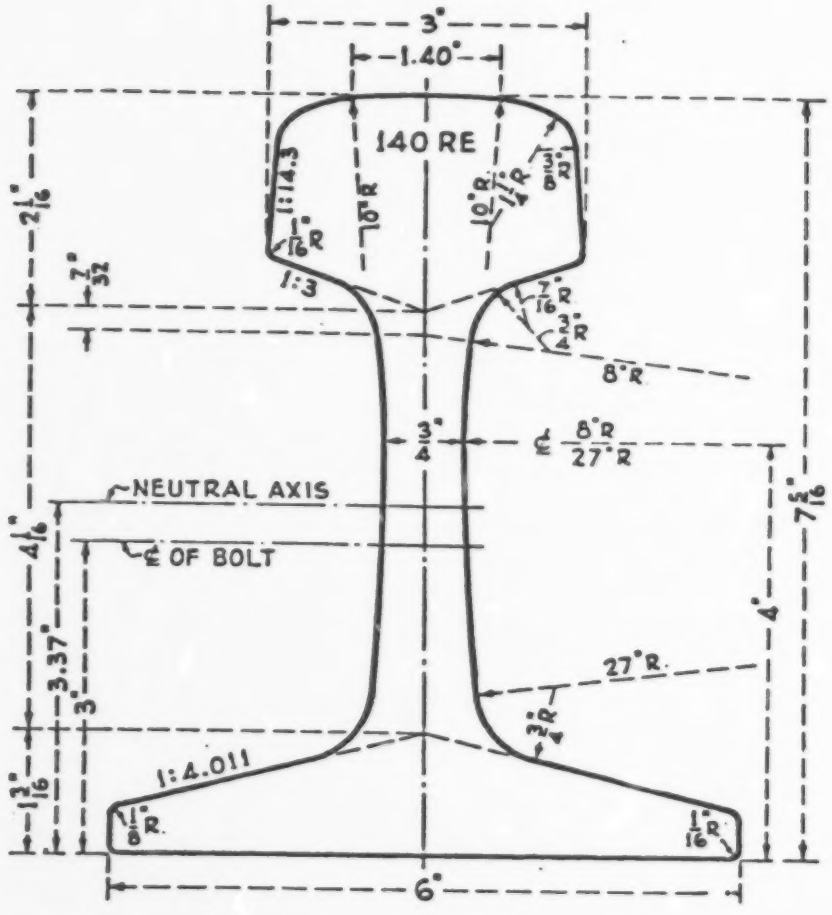
Fig. 6—136 RE rail section.

References, Vol. 63, 1962, pp. 498, 768.

(1971)

1962

(Reapproved without change 1962)



	Area Sq In	Percent
Head	5.0	36.7
Web	3.9	28.0
Base	4.9	35.3
Total	13.8	100.0

Moment of inertia	96.8
Section modulus, head	24.6
Section modulus, base	28.7
Ratio m.i. to area	7.0
Ratio s.m. head to area	1.78
Ratio height to base	1.22
Calculated weight, lb per yd	140.6

Fig. 7—140 RE rail section.

References, Vol. 53, 1954, pp. 775, 1098; Vol. 63, 1963, pp. 500, 768.

(1971)

POOR

QUALITY

ORIGINAL